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A Multithreaded Missions and Means Framework (MMF) Concept Report

by Peter J. Grazaitis and Brian G. Ruth

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A Multithreaded Missions and Means Framework (MMF) Concept Report

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14. ABSTRACT

This report addresses the problem of identifying critical knowledge elements that are essential to decision making and that impact mission outcome. All too often, these knowledge elements and their criticality to mission outcome are discovered after some catastrophic event, where (in hindsight) the Army discovers that if it only knew this or that, a decision maker would have had the information to take an appropriate course of action to mitigate or prevent mission failure. To facilitate a solution to this problem, the military Missions and Means Framework was extended from its original single-threaded structure (addressing combat operations) to a multithreaded/multiple-domain structure (addressing logistics, transportation, engineering, and intelligence in conjunction with combat operations). Finally, the operational utility of this extended multithreaded methodology is demonstrated via a notional two-threaded combat operations/logistics mission simulation using an agent-based modeling and simulation platform.

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1. Introduction

In a military context, operational forces require a robust approach for assessing their readiness to perform their missions. In such a context, the interactions and relationships between such missions and the means required to execute those missions are omnipresent in all varieties of military operations. To address this need, the Missions and Means Framework (MMF) provides an intellectual structure for explicitly specifying a military mission and quantitatively evaluating the matching of military tasks associated with the combat operation in question to the military means required to successfully achieve those operational objectives (Deitz et al., 2003; Deitz et al., 2009; Nelson and Bely, 2006; Sheehan et al., 2004). Because tasks, which are the building blocks of missions, are pulled from authoritative sources such as *The Army Unified Task List* and the *Universal Joint Task List* (Headquarters, Department of the Army, 2003; Chairman of the Joint Chiefs of Staff, 2008), commonly accepted terminology and definitions are built into the framework. Components, which represent the means used to execute tasks, are similarly derived from authoritative sources. As a result, the natural application of MMF has been within the context of Blue force vs. Red force combat operations planning and analysis (figure 1). The MMF methodology is thus used to develop tasks (and associated materiel/personnel-based capabilities required for effective task execution) for each of the opposing forces. MMF level 1 is where the opposing forces are linked via interforce battlefield threat interactions (ballistic, electronic warfare, etc.) between friendly and enemy entities. These battlefield threat interaction effects can be examined through a variety of model simulation tools to determine favorable or unfavorable outcomes. In this sense, the MMF provides traceability back through the seven MMF levels so that unfavorable outcomes at the interaction level (i.e., level 1) can be traced back to materiel or personnel state changes (i.e., level 2) and then up to specific task "readiness" states and/or capability states (i.e., levels 4 and 3, respectively) that led to the unfavorable interaction(s).

To date, the MMF abstraction has been limited to the modeling and analysis of Blue on Red force interactions (i.e., a two-thread interaction process). In reality, the Blue force is actually made up of multiple military threads (i.e., domains) that must interact successfully with one another to achieve mission success. Because of changing dynamics on the battlefield, the Blue force often has to change task and reorganize to support the often subsequent changes to the Blue force commander's mission intent. We contend that, with minor changes, the MMF could support the modeling, simulation, and analysis of multiple dual-thread interactions between cooperating Blue force domains, such as logistics assets and combat operations forces, logistics assets and transportation assets, combat operations forces and intelligence assets, and so on. In reality, all of these domains interact simultaneously through the execution of a mission plan.

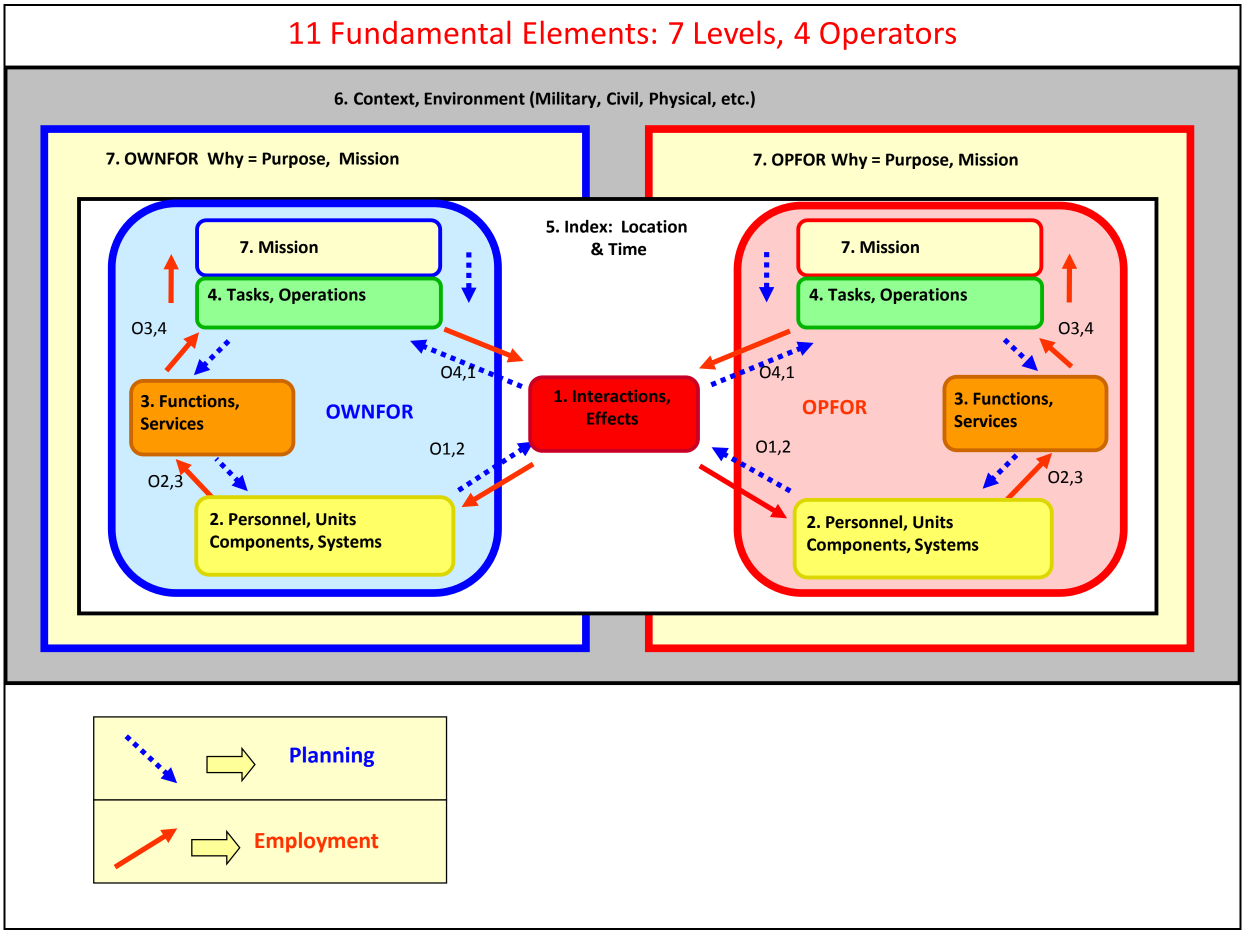

Figure 1. MMF as applied to the military combat domain.

Thus, we believe the key question in addressing this multithreading issue is, How do we extend the MMF to support many simultaneously interacting threads? In other words, what does the multithreaded MMF abstraction look like from a theoretical perspective? More importantly, how does one construct an agent-based modeling and simulation (ABMS)* tool to implement a multithreaded MMF concept that is representative of a real mission, wherein many military domains simultaneously interact to represent the various mission-oriented activities the Blue force is engaged with internally as the mission progressively executes and unfolds over time? In addition to considering many different military domains, this ABMS implementation must also represent many interacting agents acting as various domain commanders making decisions based not only upon their own task outcomes, but also on outcomes of tasks executed within other cooperating domains.

*Agent-based modeling and simulation refers to a class of computational models for simulating the actions and interactions of autonomous agents (both individual and collective entities, such as organizations or groups) with a view to assessing their effects on the system as a whole. It combines elements of game theory, complex systems, emergence, computational sociology, multiagent systems, and evolutionary programming (North and Macal, 2007).

2. Single-Threaded MMF Modeling

In general, every conceivable purpose-oriented and goal-driven military mission requires a disciplined procedure to explicitly specify a military mission, allocate Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities (DOTMLPF) means to execute that mission, and assess mission accomplishment. In a procedural sense, the connection between a military mission and the means required for its execution is formally expressed via the mission-to-materiel trace (figure 2) (Bray, 2006). Using this process, a warfighter designing a mission can describe

- how a particular mission is made up of tasks (assigned to units, platforms, and dismounts),
- how each task is enabled by a set of one or more capabilities, and
- how each capability is supplied by the functioning of a set of materiel elements or components.

Once the mission has been designed, the mission-to-materiel trace can also describe

- how materiel elements/components collectively work together to provide systemic functions,
- how materiel functions in turn work together to provide system (or system-of-system)-level capabilities,
- how capabilities collectively serve to provide a means to perform tasks, and
- how tasks collectively provide a means to accomplish the intended mission.

Once a set of capabilities is proven to exist, the warfighter knows which tasks are enabled and which materiel properly contributes to mission success. Additionally, knowing the standards to which tasks must be accomplished assists in driving appropriate performance requirements to ensure that available materiel provides capabilities in an operationally realistic environment.

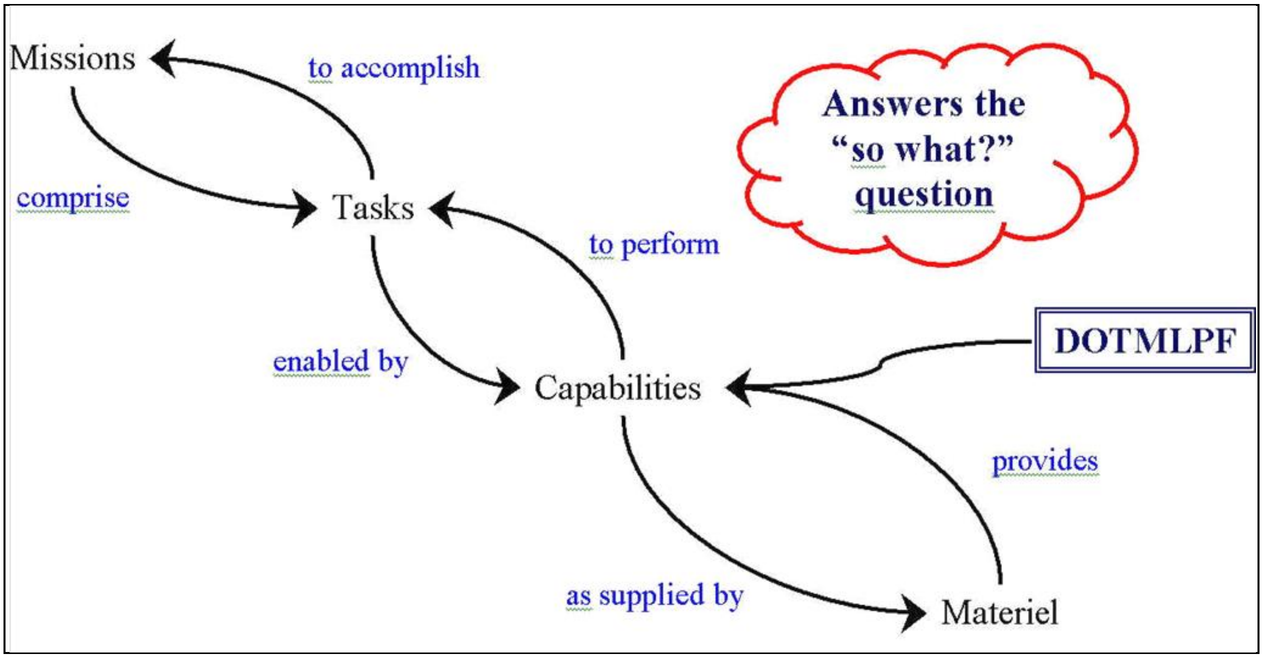

Figure 2. The mission-to-materiel trace that associates the mission-to-task decomposition process with supporting capabilities and materiel.

By expanding the mission-to-materiel trace into a two-sided decision-making process involving both friendly and enemy combat forces, we arrive at the MMF: a methodology for explicitly specifying a military mission and for quantitatively evaluating the mission utility of alternative warfighting DOTMLPF products and services (Deitz et al., 2003; Sheehan et al., 2004). As previously introduced in section 1, figure 1 illustrates the elements that collectively define the MMF. To specify the mission, the MMF first employs a top-down planning process (i.e., the dashed blue arrows in the figure) that begins with an analysis of the operational mission to be performed by a military system or system-of-systems. The analysis results in identifying the following key elements at several levels of abstraction:

- Level 7 includes the task, purpose, and desired end state of the mission.
- Level 6 describes the operational context (i.e., civil/political, military, and environmental conditions) within which the mission is to be conducted.
- Level 5 specifies the space/time index within which the mission is conducted (i.e., the interval of time extending from the initial road to war to the conclusion of all operating environment activities).
- Level 4 identifies the operations and tasks that must be performed in order to accomplish the mission.
- Level 3, in turn, identifies the capabilities and functions that contribute to the successful performance of the operations and tasks identified in level 4.

- Level 2 then identifies the materiel/components that deliver the associated functions and capabilities identified in level 3.
- Level 1 describes the necessary interactions that must be generated in order to achieve the desired effects.

Ideally, this planning process results in an executable mission thread of task/component combinations that are sequenced and interrelated from the planned start of the mission to its successful completion (achieving the desired end state). These mission threads represent a model of the warfighter's concept of the operation that would normally be captured in the form of an execution or synchronization matrix. Finally, the planning of mission threads within the MMF is a dual process, with Own Force (OWNFOR) (Blue/friendly force) mission planning competitively and concurrently counterbalanced by Opposing Force (OPFOR) (Red/enemy force) planning.

To execute and assess the OWNFOR and OPFOR mission threads, the MMF also provides for a bottom-up employment process (i.e., the solid red arrows in figure 1) that complements the top-down planning process. This second MMF process facilitates combat adjudication once mission threads have been configured for all battlefield forces, resulting in the observation and capture of information at seven different levels of abstraction (two of which levels typically remain unchanged from the top-down planning process described in the previous paragraph). This level-specific information includes the following:

- Level 1 identifies the interactions taking place between operational entities (combatants and indigenous noncombatants if present) and the resulting combat effects achieved.
- Level 2 descriptively enumerates the state changes in components and forces resulting from the combat interactions identified in level 1.
- Level 3 subsequently identifies the residual levels of function and capability available to operational entities as a result of changes in component/force state.
- Level 4, in turn, describes the follow-on state of task execution "readiness" by first evaluating the combat effects achieved thus far to those desired, and then comparing the capabilities required to achieve successful task execution to those capabilities perceived to be currently available for use by the warfighter.
- The level 5 space/time index within which the mission is conducted was originally set during the top-down planning process and thus remains unchanged during the employment process (unless a replanning process is required, upon which event the space/time index might change).

- The Level 6 operational context within which the mission is to be conducted was originally set during the top-down planning process and thus remains unchanged during the employment process (unless a replanning process is required because of an unexpected change in the operational context, e.g., a civil uprising).
- Level 7 involves a dynamic comparison of perceived operating environment conditions to desired mission end state as perceived by the force commander (a continuous process until the latter decides that the desired mission end state has been achieved or that a mission replanning process is required because of an unexpected change in the operational context).

Once key information residing in levels 4 and 7 is assessed and acknowledged by a force commander, the MMF employment process provides a means for the commander to provide critical guidance (e.g., new orders, stay the course) to all operational entities under his/her control regarding subsequent interactions with other enemy entities. Finally, as with mission planning, it must be noted that combat employment of mission threads within the MMF is a dual process, with OWNFOR employment again competitively and concurrently counterbalanced by OPFOR employment.

A depiction of both the top-down planning and bottom-up employment processes reflecting current and established MMF applications is presented in figure 3.

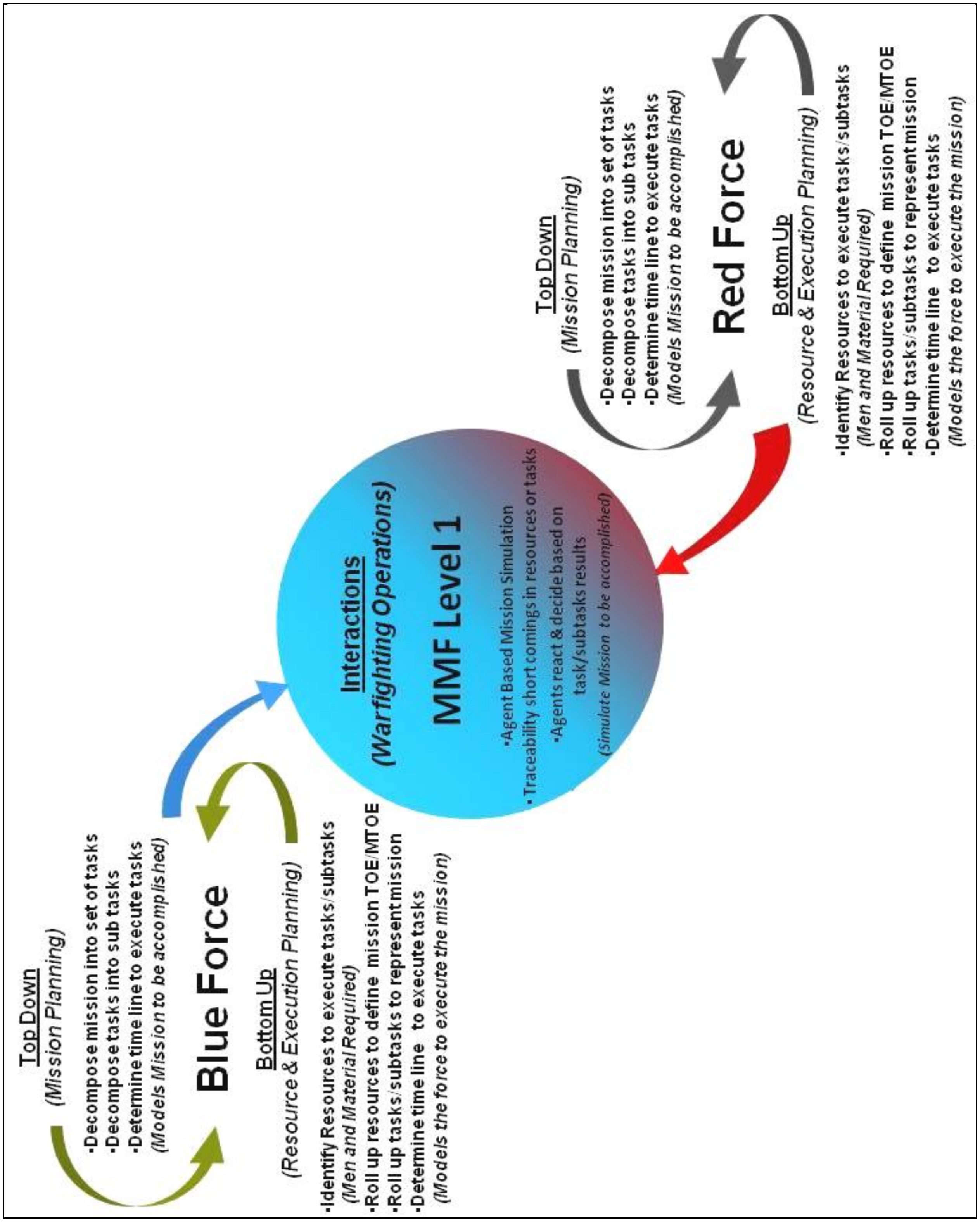

Figure 3. Current application of MMF.

3. A Multithreaded MMF Model for Concurrent Operations in Complementary Domains

In computer science, a *thread* is a computational process that typically runs concurrently alongside one or more other computational processes as a function of time (Lewis and Berg, 1995). Given a multiprocessor or multicore computational system, these threads or tasks will generally run at the same time, with each processor or core concurrently running a particular thread or task. In the same context, *multithreading* allows multiple threads to exist within the context of a single overall process. These threads share the process' resources but are able to execute independently. From an operational perspective, one particular advantage of computational multithreading is the ability for a software application to remain dynamically responsive to input. In a single-threaded program, if the main execution thread becomes blocked, the entire application can appear to freeze. If we move tasks to another thread that runs concurrently with the main execution thread, it is possible for the application to remain responsive to user input while executing tasks in the background.

In a military context, we can apply multithreading to the MMF. As previously mentioned in section 2, the current MMF structure is designed to address a two-threaded process involving primarily Blue on Red force interactions. In reality, the Blue force is actually made up of multiple military threads (i.e., domains) that must interact successfully to achieve mission success. Because of changing dynamics on the battlefield, the Blue force often has to change task and reorganize to support corresponding changes in the Blue force commander's intent. With some minor modifications, we will illustrate how an extended MMF structure could readily support the design of dual-threaded military domain interactions, such as logistics assets and combat operations forces, logistics assets and transportation assets, combat operation forces and intelligence assets, etc.

In reality, all these domains interact simultaneously through the execution of a mission plan that reflects the operational intent and purpose(s) of the mission commander. Figure 4 depicts a conceptualization of the existing MMF structure extended to four concurrently operating military domains (i.e., logistics, transportation, combat operations, and intelligence). Here, each thread represents a Blue (friendly) operational domain that can interact with one or more other Blue domain threads via the MMF level-1 space. What the structure in figure 4 really attempts to illustrate is the flow of the military domain specific decision-making processes that unfold as various domain commanders dynamically make decisions based not only on their own task outcomes, but also on outcomes of tasks executed within other complementary Blue force domains. Thus, this abstraction, in a general sense, is representative of a real mission and many military domains cooperatively interacting simultaneously to represent what the Blue force is doing internally as the mission executes.

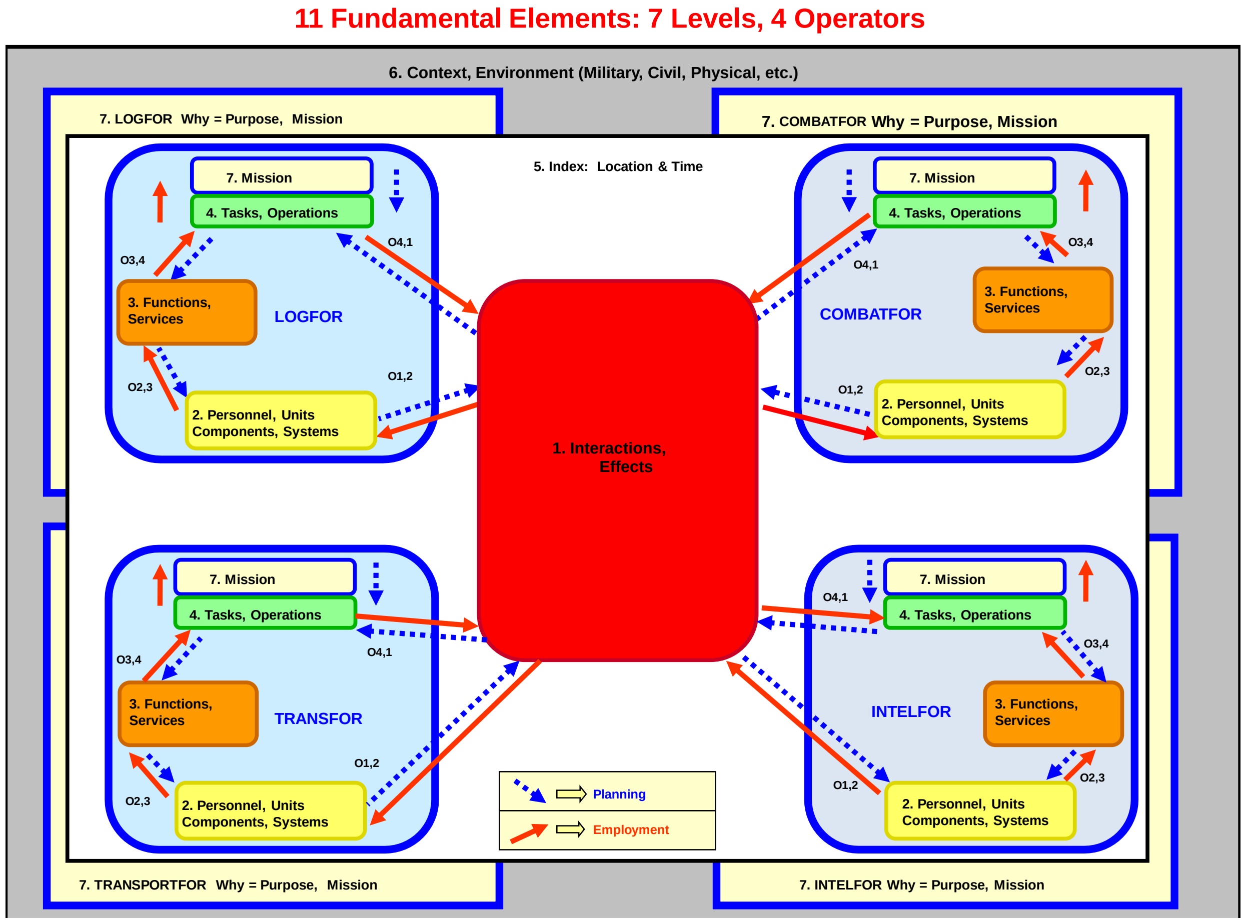

Figure 4. Conceptualization of the multithreaded MMF abstraction as concurrently applied to the logistics, transportation, combat operations, and intelligence military domains.

Next, figure 5 depicts the natural multithreaded extension of the original combat-operations-oriented matching of military tasks to necessary military means shown in figure 3. As was the case in the two-threaded Blue force vs. Red force MMF, tasks are again the building blocks of multithreaded Blue activities across cooperating military domains and thus must also be pulled from authoritative sources. However, in the multithreaded MMF context, the means used to execute tasks will now be a function of those specific capabilities required for task execution within each of the cooperating Blue military domains. Examples of such domain-specific means could be (1) trucks for transporting needed equipment in the transportation operations domain, (2) pipeline networks for moving needed fuel in the logistics operations domain, and (3) multimodal materiel sensor and human social networks in the intelligence operations domain.

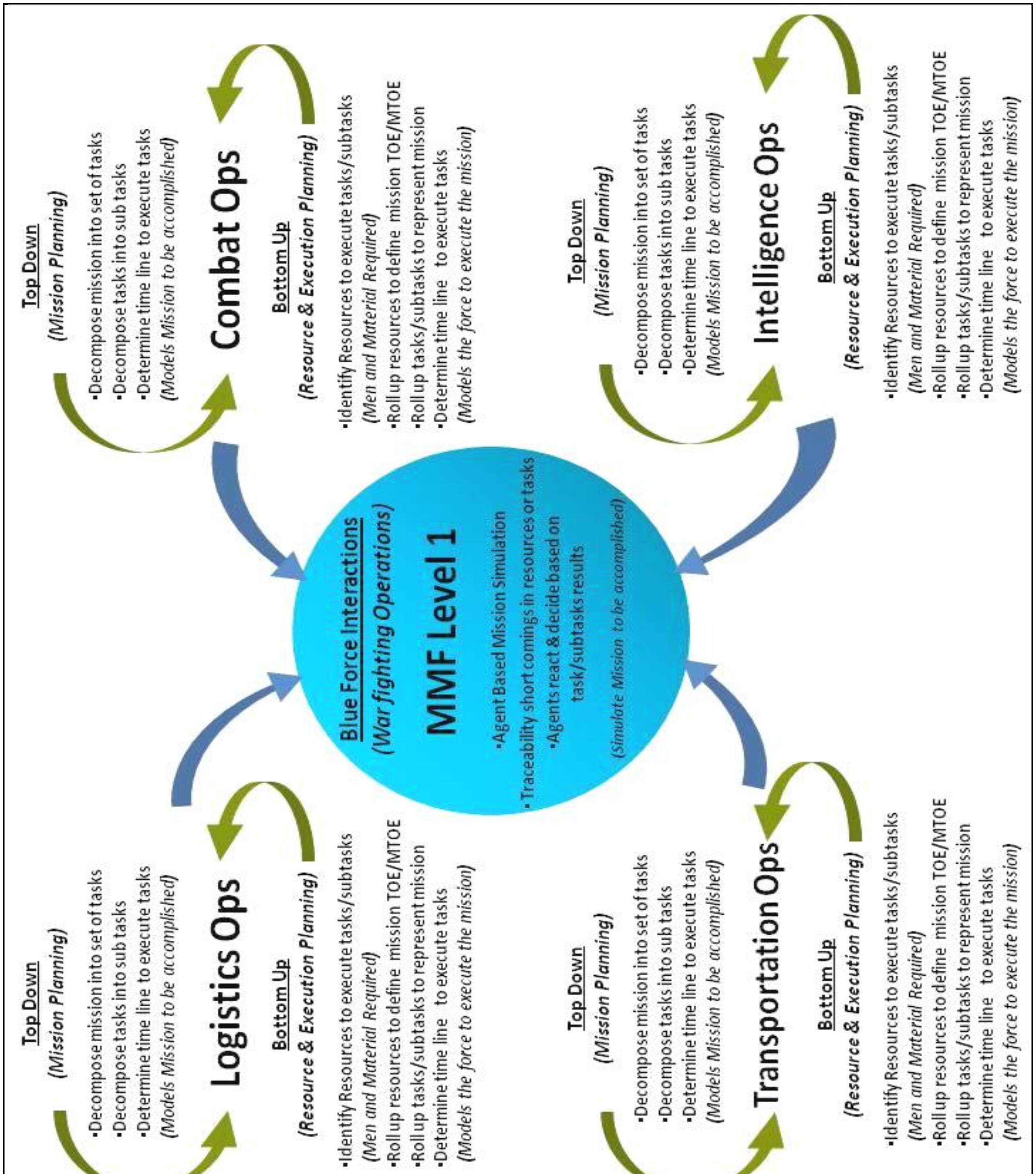

Figure 5. Multithreaded application of the MMF.

Perhaps the biggest adjustment from the single-threaded to multithreaded MMF structure lies in the nature of level 1-interactions. In the multithreaded case, these interactions represent the overall Blue force business process, where cooperating and complementary military domains are linked via the simulation of concurrent product- and service-oriented exchanges between one or more providers within one domain and the corresponding product and service customers within the receiving domain. In a manner similar to the battlefield threat interaction effects emerging in the original combat operations MMF, the multidomain Blue force business process effects can be examined through a variety of model simulation tools, again with the objective of determining favorable or unfavorable outcomes. But in this case, these outcomes can now be analyzed to reveal the cause-and-effect relationships between successful (or failed) interdomain product and service exchanges at the interaction level (i.e., level 1), subsequent materiel/personnel state changes due to delivered (or undelivered) materiel products and services within the customer domain (i.e., level 2), and then up to specific capability and task "readiness" states (i.e., levels 3 and 4, respectively) that can lead to resulting favorable (or unfavorable) overall mission outcomes at the Blue force level (i.e., level 7).[*]

Having introduced the notional structure of the multithreaded MMF, we now define a useful *ontology* or "formal specification of a shared conceptualization" (Borst, 1997) that describes the multithreaded MMF in a practical fashion. Such an ontological description should prove to be both computationally tractable to a software agent seeking to use the multithreaded MMF for decision-making purposes and also conceptually accessible to all decision-making entities (both humans and software agents) seeking to work together under a shared mission context. We base our ontology upon the concepts of generalized mission and materiel/personnel hierarchies, as illustrated in figure 6. Here, on the one hand, the MMF addresses the analysis of a mission as a top-down process that decomposes a mission into (1) a collection of operations required to accomplish that mission and (2) collections of tasks (where each collection is assigned to a specific operation within the mission) having specific capability requirements to ensure proper and effective task execution within an operation. On the other hand, the MMF embraces a complementary bottom-up hierarchy that defines a set of system or platform capabilities as a composition of lower-level functions provided by elementary components and/or subsystems (which can include hardware, software, and personnel). Thus structure naturally implies a necessary linking between the capabilities formally required to guarantee task execution (to then ensure mission accomplishment) and the available capabilities provided by available systems (Minchew, 2006).

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[*]In the case of an overall Blue force combat mission against an enemy Red force, the multithreaded MMF structure would also include an additional level-1 interaction thread between the Blue combat operations domain and the Red force. In this type of situation, the Blue combat operations domain actually engages in *two* different modes of level-1 interactions: (1) battlefield threat interactions with the Red force (representing the "traditional" two-sided Blue/Red interaction MMF) and (2) product and service business interactions with the remaining Blue military domains (whose submission is to provide critical support to the primary combat operations domain directly engaging the enemy).

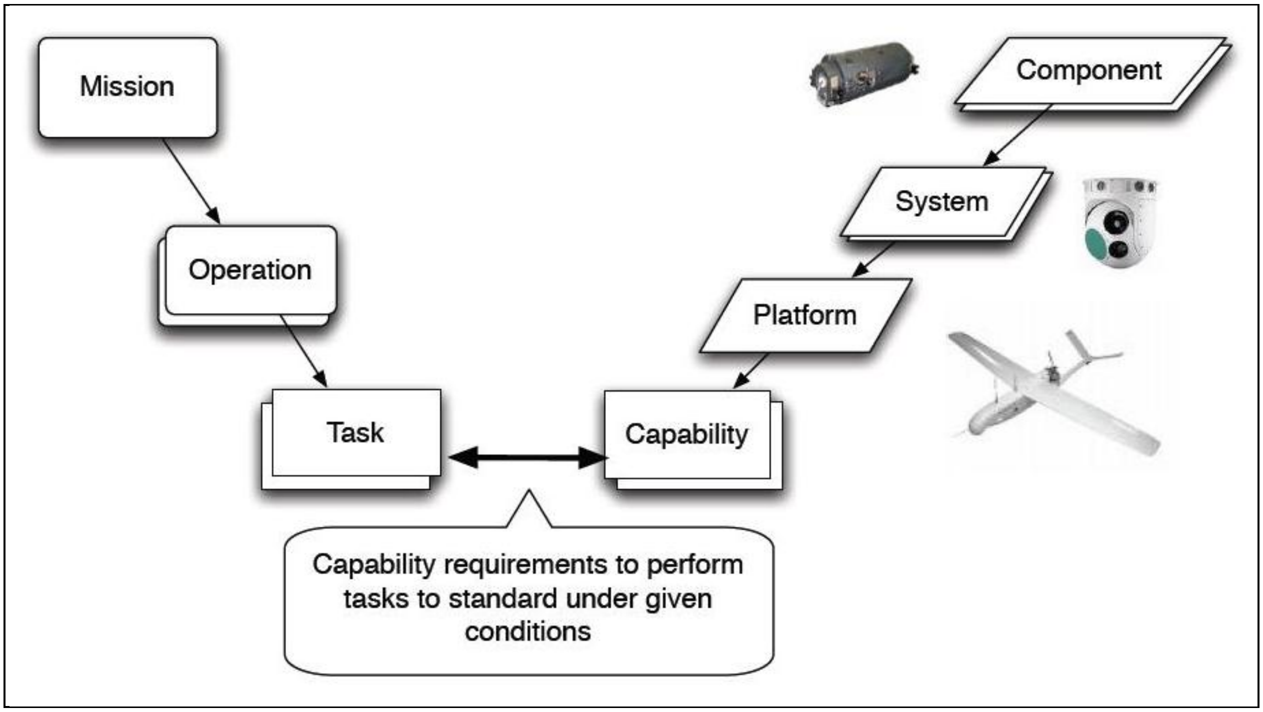

Figure 6. Generalized mission and materiel/personnel conceptual hierarchies describing the linkage of "missions" and "means" within the MMF (Minchew, 2006).

Next, in figure 7, a generalized MMF ontology as first proposed by Preece and associates (Gomez et al., 2008; Preece et al., 2007; Preece et al., 2008) is presented. Given that the MMF is basically a collection of concepts and associated properties allowing a military planner to reason about the requirements of a mission and the means required to accomplish it (e.g., mission, task, capability, asset), this formalized expansion of the MMF structure in figure 6 into the ontology seen in figure 7 is very straightforward. On the left-hand side, we have the concepts related to the mission: a *mission* comprises several *operations*, each of which comprises several *tasks* that need to be accomplished. On the right-hand side, we have the concepts related to the means. A *component* is a constituent element within a *system* that can be carried by or constitute part of a *platform*, and inversely, a platform can accommodate or mount one or more systems. Both platforms and systems are *assets*. An asset provides one or more *capabilities* (each of which can entail a number of more elementary functions) and is required to perform certain types of tasks; and inversely, a task is enabled by one or more asset capabilities.

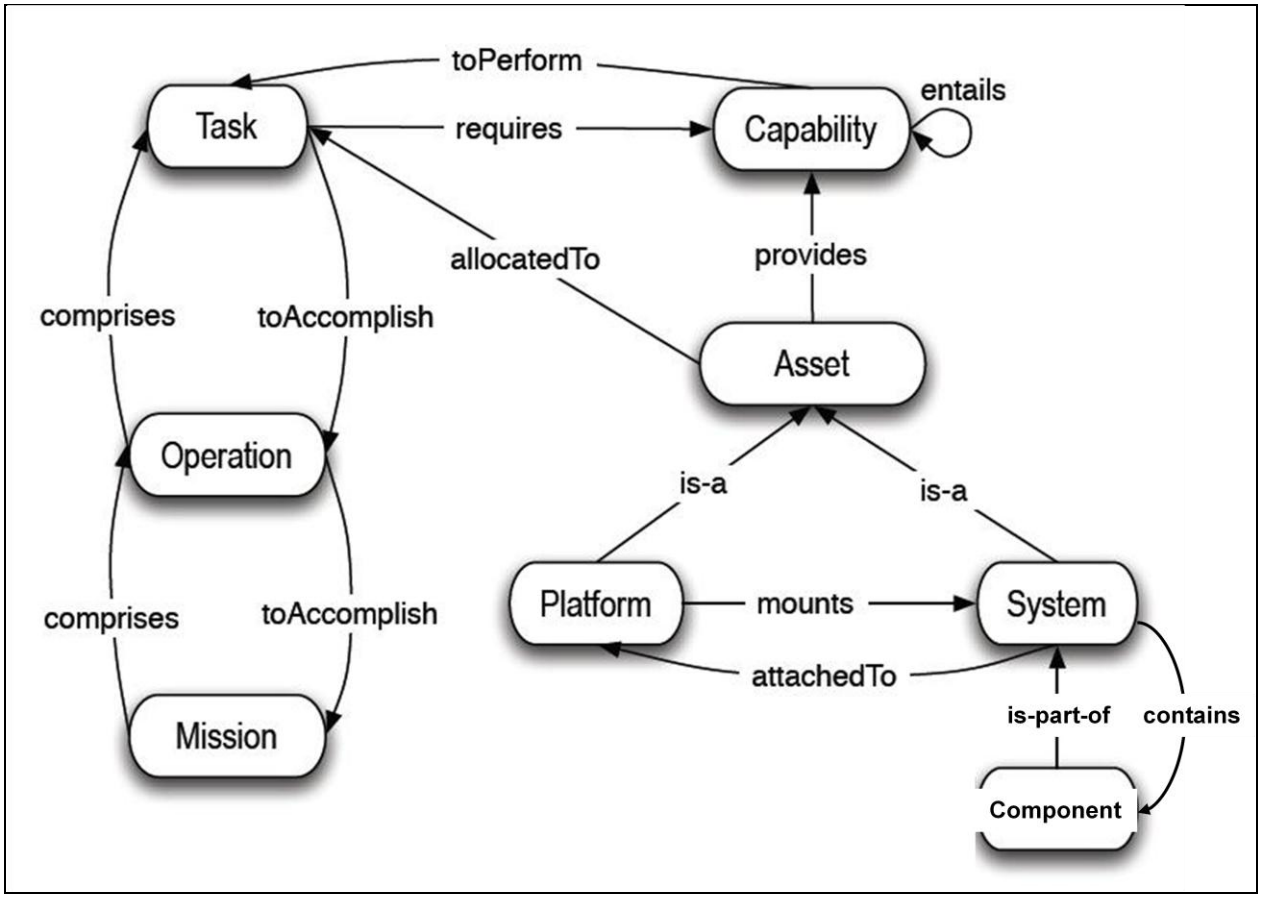

Figure 7. An MMF ontology.

Once a general multithreaded MMF structure and a general MMF ontology have been defined, we can combine and fuse these "ingredients" into a multithreaded MMF ontology. Figure 8 depicts a notional fusion of the MMF ontology with the conventional two-sided MMF structure defined for the combat operations military domain. Here, the ontological concepts characterizing a generalized military force have been embedded within both the OWNFOR and OPFOR constructs, which in turn interact via MMF level-1 combat activities. In this representation of the MMF, the ontology perspective provides valuable insight to the user on how elements making up MMF levels 2, 3, 4, and 7 within a force structure interrelate to one another. Then, as shown in figure 9, the next logical step is to embed the MMF ontology into the multithreaded structure of cooperative and coordinated military domains existing and operating within OWNFOR. From this perspective, the various elements of the multithreaded MMF business process are explicitly illustrated, wherein each military domain demonstrates a specific business objective (represented by the embedded concepts of mission, operations, and tasks), along with the corresponding means (represented by the concept of materiel/personnel assets providing required capabilities) needed to realize those objectives.

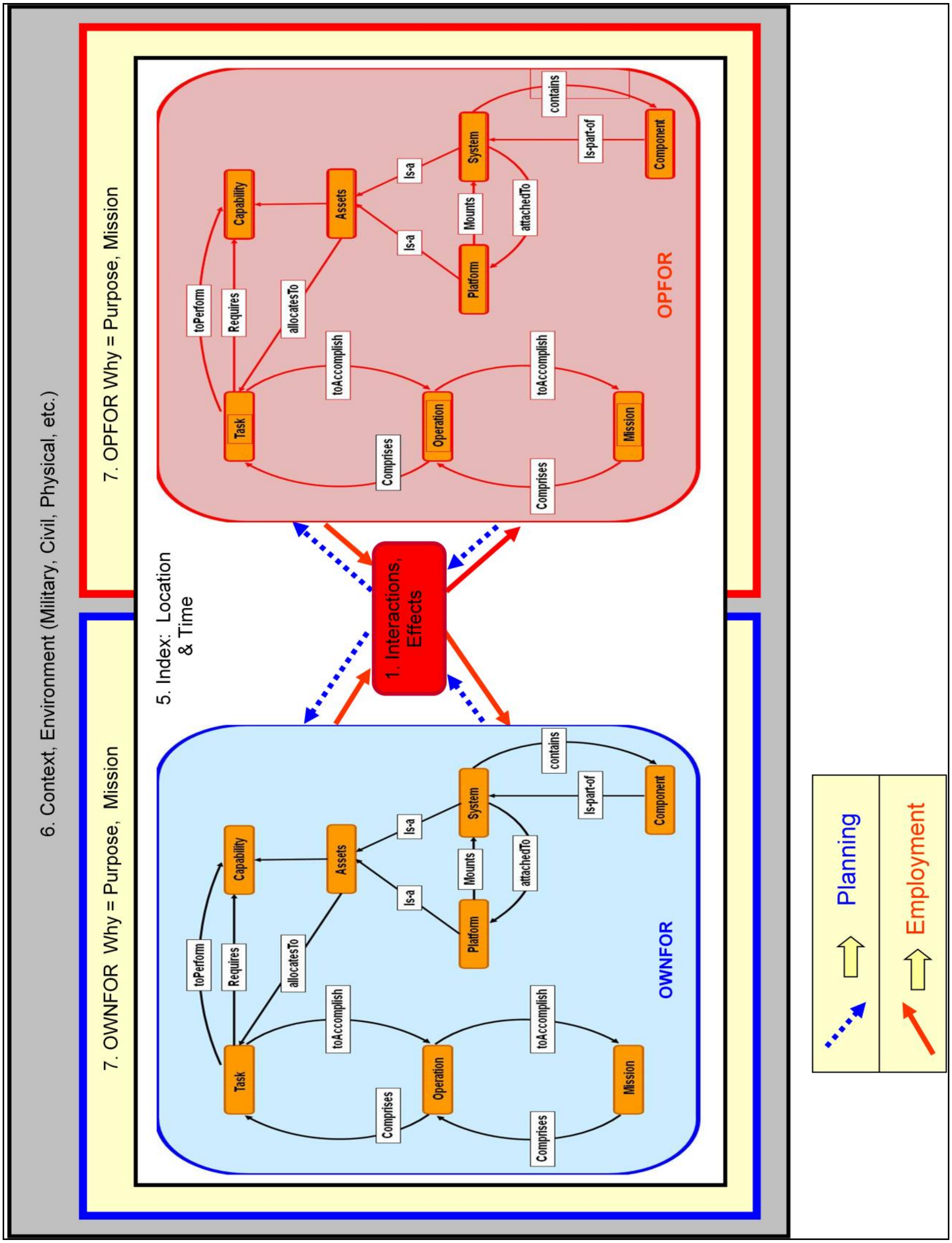

Figure 8. Embedding the MMF ontology inside the current two-threaded Blue/Red combat operations perspective.

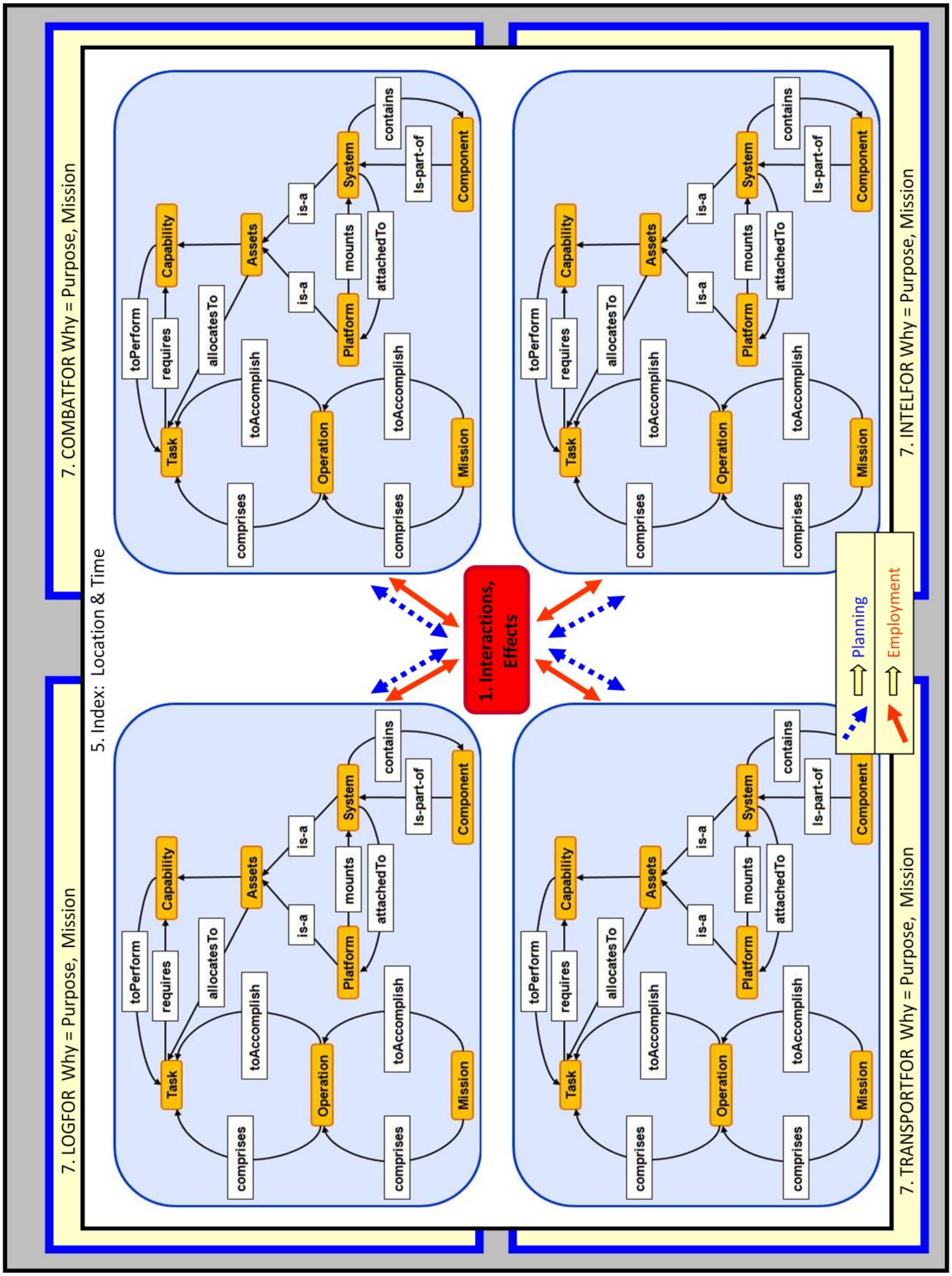

Figure 9. Embedding the MMF ontology inside the multithreaded perspective of cooperative and coordinated Blue military domains.

For a military operational thread to execute successfully within a multithreaded context, force-level mission planning must anticipate the need for this thread to often interact with other military operational threads that provide essential capabilities required at specific times (figure 10). For example, the logistical operations must plan and execute sustainment deliveries to combat operations forces for mission success to occur. This extended MMF capability configuration process will provide the planning warfighter the ability to describe and characterize the complex top-down planning process as well as the bottom-up employment process to execute and assess the complex dynamic interactions of all these military operational threads. Then, through the use of autonomous agent technology, MMF level-1 thread interaction effects can be simulated for a hypothetical mission and mission time horizon involving two or more distinct operational threads with the objective of determining favorable or unfavorable outcomes. Unfavorable outcomes at the interaction level can be traced back to material and/or personnel state changes up to specific tasks and/or capabilities that lead to an unfavorable interaction (i.e., mission failure). These state variables represent the knowledge and information elements and are critical to mission success for a given hypothetical mission.

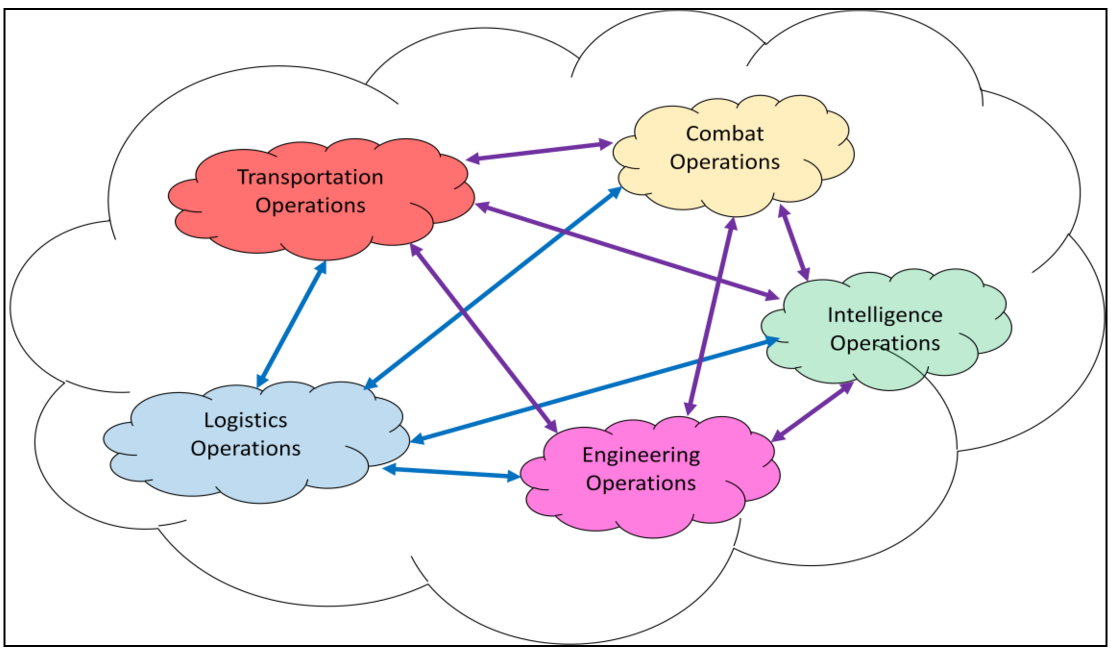

Figure 10. Coordinated planning between different cooperating mission threads within a military force. In general, planning-oriented communication channels must potentially exist between *all* cooperating military domains within the force.

4. Demonstration of the Multithreaded MMF Paradigm

As proposed in section 3, the conventional MMF can be extended to examine more than one aspect of mission operations. For example, as illustrated in figure 11, we can analyze the specific interactions between entities within the Blue force combat operations and logistics military domains that are required to ensure mission success. This type of analysis can support the overall Blue force mission by answering the question, Does my logistical mission (tasks and capabilities) support the anticipated/planned combat operational mission (tasks and capabilities)? In other words, can the logistics tempo match the combat operational tempo?

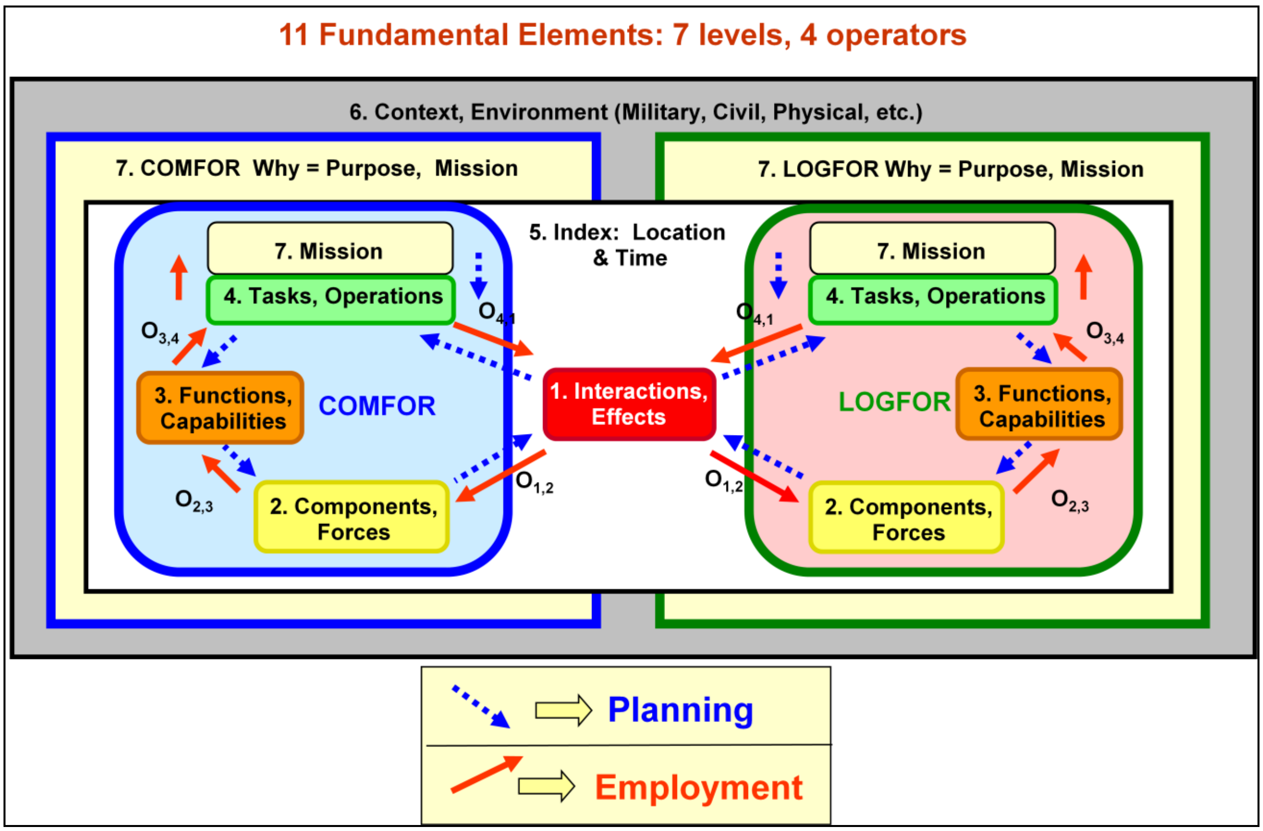

Figure 11. A two-threaded MMF model for phase matching mission and sustainment needs.

These types of thread interactions within a larger multithreaded MMF context can be modeled and simulated using agent-based software tools to examine the complex dynamic decision-making processes that exist among the threads when logistical and combat operational interactions occur during the planning, deployment, and execution of a military mission. In this section, we present and analyze such a notional scenario.

The details of an operational vignette illustrating a notional interaction between logistics and combat operations assets are presented in section 4.1. The results of simulating this demonstration vignette using an ABMS software package are presented and discussed in section 4.2.

4.1 Demonstration Vignette

This section presents an operational vignette describing a notional mission-supporting cooperative and collaborative interaction between Blue force logistics and combat operations assets. This vignette was originally constructed by technical personnel with the U.S. Army Logistics Innovation Agency as part of their Enterprise Based Approach to Logistics (EBAL) Project in 2007 (Gardner, 2007; Mitchem, 2007). The EBAL vignette is, in turn, drawn from the U.S. Army Combined Arms Support Command's (CASCOM's) Modular Force Logistics Concept (MFLC) scenario.

4.1.1 General Operational Situation

The general operational situation is as follows. There is political and social unrest between the notional Middle Eastern nations of Ageori and Janazer (figure 12). Ageori is a secular state with close ties to the west, especially the United States; Janazer, however, is an extremist state. Extremist organizations operating within Janazer have instigated anti-U.S. sentiment in the region and have sponsored insurgencies into Ageori. Deterioration of political and diplomatic approaches is imminent. Ageori is expected to request help from its Western partners. Viewed as a possible area of deployment, the Joint Force Commander (JFC) decided to insert Special Operational Forces (SOF) into the area of operations (AO) through and with the support of the government of Ageori. Conditions continue to deteriorate, as insurgents resort to assassinations and the use of improvised explosive devices (IEDs) throughout Ageori to instill fear and destabilize the Ageori government. Insurgent forces quickly establish a foothold in the east and continue in their efforts to gain control of the eastern region of Ageori. Ageori requests assistance in restoring its territorial integrity and the rule of law.

While tensions increase in Ageori, the JFC's planners tailor the force through mission analysis. With the support of the government of Ageori, they have established a Joint Special Operations Task Force near Lochini. The purpose of the deployment was to gain a positional advantage, prepare and shape the operational area and environment, set conditions which mitigate risk, and facilitate successful follow-on operations. The JFC has directed the Theater Sustainment Command (TSC) to provide support to the SOF deployed to the Joint Operations Area (JOA). The chain of command notifies three brigade combat teams (BCTs) and one air cavalry brigade to deploy and begin final preparations for movement. Modular units are configured and organized. Planners coordinate for strategic lift and prepare/adjust time-phased force deployment data to meet the Blue force theater commander's needs. Additionally, the JFC has requested the Defense Logistics Agency to establish a forward Defense Distribution Center, with a theater containerization and shipping point to be established near Topo.

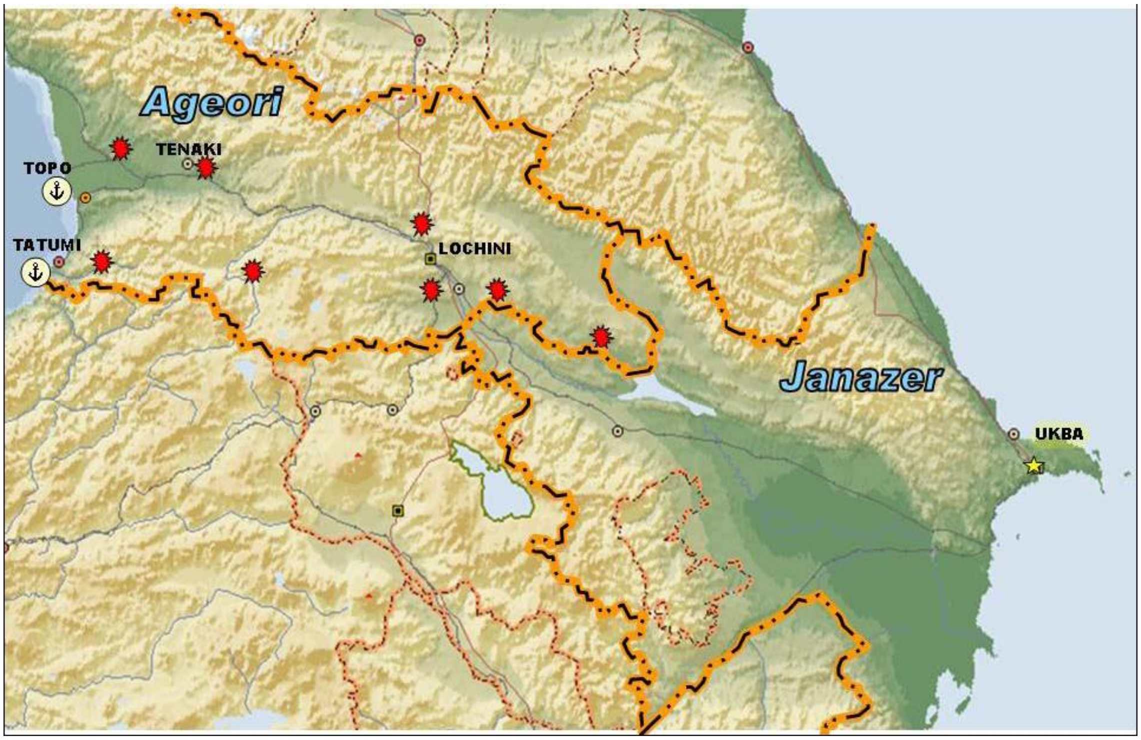

Figure 12. Area of regional conflict for the demonstration vignette.

This scenario is played out under the MFLC featuring sustaining operations provided by a TSC. Under the MFLC, an Army Sustainment Command (ASC) coordinates the establishment of essential network links between the TSC, Army and joint providers, and the JFC. The ASC also supports the Forces Command in rapid deployment of forces from CONUS to the theater of operations. The TSC designates forces and deploys modular capabilities in support of JFC sustaining operations. An Expeditionary Sustainment Command (ESC) is one of the TSC deployable command elements. The mission of the ESC is to provide a TSC forward command and control (C2) presence in a specific region or the JOA at the TSC level. The ESC, by being the TSC in theater presence, becomes the TSC for operational purposes. Consequently, the ESC executes operational control of Army or joint forces performing logistic functions within the JOA.

For this operational scenario and associated vignette, the ESC was deployed along with theater sustainment brigades, as depicted in figure 13, in support of the initial shaping operations and subsequent sustaining operations. Within the ESC, the critical focus is on the support operations (SPO) whose mission is to establish and to maintain the Army portion of the theater distribution system and sustaining force in accordance with the JFC's priorities and intent. The TSC established a distribution hub near the town of Lochini near tactical assembly area (TAA) Liberty that employs host nation, contractor support, and Army assets to effectively provide logistics support using multimodal means of distribution (including air, truck, and rail transport).

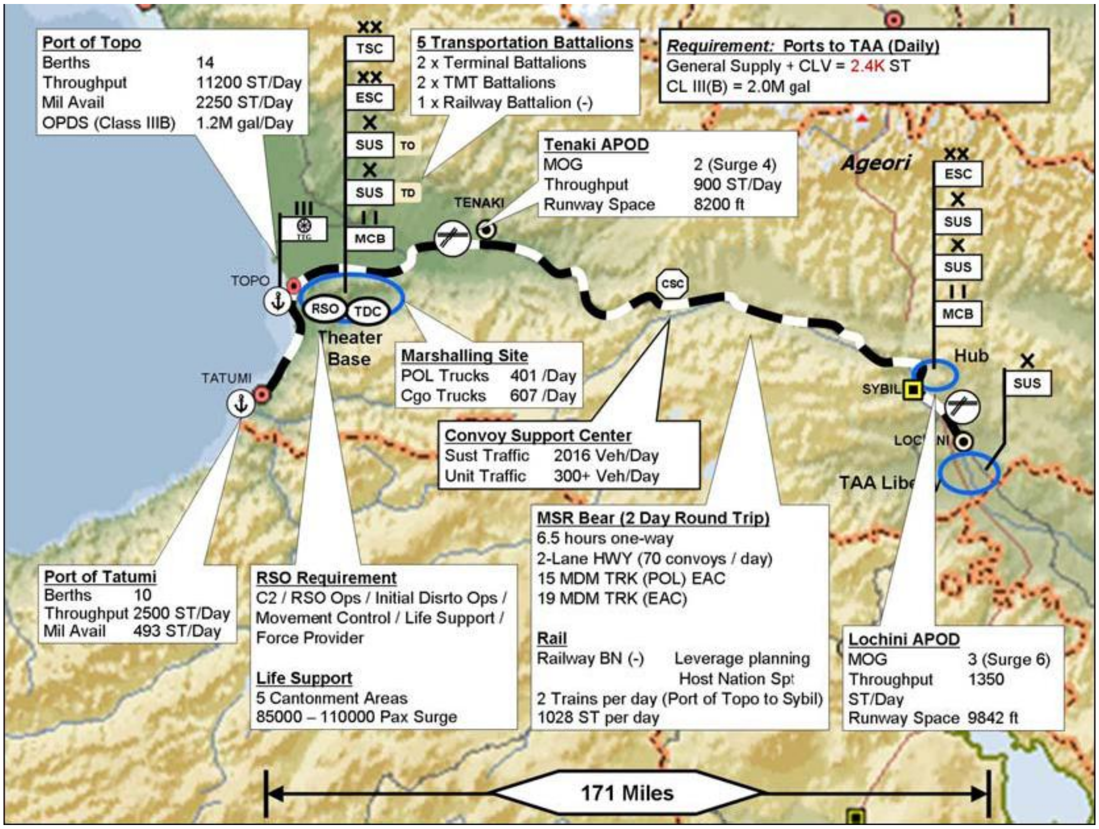

Figure 13. Strategic-level illustration of the ESC within the demonstration theater of operations.

Within the ESC, the Theater Sustainment Brigade Opening (TSB(O)) performs the theater opening functions (e.g., establishing holding, staging, and marshalling areas; life support; and distribution operations) and is responsible for C2 of multiple transportation motor transport battalions and combat sustainment support battalions in support of its reception, staging, and onward (RSO) movement mission. It is also responsible for coordinating, synchronizing, and clearing aerial or sea port of debarkation (APOD/SPOD) holding areas, staging areas, and marshalling areas; personnel and unit equipment integration; life support; security; and the multimodal onward movement of units and/or supplies to the TAA and/or distribution hubs. The TSB(O) requires close coordination with the supported commander, TSC, joint partners, and host nation.

Also within the ESC, the Sustainment Brigade for Theater Distribution (TSB(D)) is another critical element of multifunctional support operations that includes air, land, and sea operations; management of materiel; management of assets; developing requirements and priorities; and synchronization with the capability to perform retrograde functions critical to the repair of vehicles, equipment, weapons, and components. Critical logistics support tasks include synchronizing multinodal, multimodal distribution operations across a distributed battle space in support of JFC requirements; maintaining visibility of the distribution system; and distribution management. Specific functions inherent to the TSB(D) are the establishment, operation, and

C2 of the distribution hubs; distribution management; and physical distribution: receiving, processing, storing, transloading, configuring materiel and equipment, and multimodal distribution of supplies and equipment. The TSB(D) is also responsible for planning, establishing, and maintaining the distribution system in coordination with the TSC.

Janazer continues to instigate anti-U.S. sentiment in the region, while Ageori has requested help from the United Nations and its Western allies. The JFC directed the TSC to provide support to SOFs deployed to the JOA. Having anticipated the rise in aggressive actions by the extremists, the Blue force theater commander has issued an operations plan 06 for the XX Division and YY BCTs and Coalition Brigade to be deployed to the AO. A Marine Expeditionary Unit (MEU) will be deployed in and around the ports of Topo and Tatumi to provide local security for the TSB(O). The MEU, supported from a sea base, will conduct operations without disrupting RSO operations at the theater base located east of the port of Topo.

The scheme of distribution will be for the TSC SPO to supervise the external mission support requirements within the AO, thereby executing the logistics support, as translated from the commander's operational mission/tasks into priorities of support. TSC assumes responsibility as the single proponent in the AO for distribution and maintaining visibility of the distribution system. The TSC's primary mission is to synchronize and integrate logistics operations into the maneuver commander's battle rhythm to build and sustain combat power during decisive operations. It is assumed for this demonstration that a robust communications network links the TSC with Army and service planners, as well as SOF and joint partners, horizontally and vertically, thereby enabling effective command and control.

4.1.2 Specific Description of the Vignette

The Blue force theater commander has issued fragmentary order (FRAGO) 06-01 indicating that the First Cavalry Division (1st Cav Div) will follow the MEU and other coalition brigade forces in theater. This FRAGO indicates an increased operational tempo for 1st Cav Div, which has resulted in an upgrading of its mission/task priority ranking with respect to the rest of the deployed Blue force. A subsequent operational status review by the associated division commander indicates that 1st Cav Div is below the mission-required 90% operational readiness condition because of several factors.

- There is a shortage of class III supply items, which specifically includes supplemental fuel that will be required by ~25–30 Bradley M2 vehicles within a battalion in the division.
- There is also a shortage of class V supply items, which specifically includes supplemental ammunition required by ~20–25 other Bradley M2 vehicles within the same battalion.
- Finally, there is a shortage of a critical class VII supply item: an additional Bradley M2 vehicle is required by the same battalion to replace an existing vehicle rendered dysfunctional by extensive combat damage.

To address this shortfall, the TSC Operations Cell Battle Captain recommends a course of action (COA) where the fuel supplies, ammunition supplies, and Bradley M2 vehicle currently undergoing transport into theater onboard USNS *Benavidez* be delivered to the unit within 1st Cav Div with the higher priority. This is the battalion demonstrating the materiel shortfall specified previously.

As part of the demonstration vignette, we assume that the convoy support center (CSC) within the TSC deploys a notional supply convoy consisting of six transportation vehicles:

- Three vehicles assigned to transport class III supplies (i.e., pallets holding fuel containers loaded into the cargo bay of the transport vehicle).
- Two vehicles assigned to transport class V supplies (i.e., pallets holding ammunition packed in boxes loaded into the cargo bay of the transport vehicle).
- One vehicle assigned to transport class VII supplies (i.e., a replacement Bradley M2 vehicle mounted in the cargo bay of the transport vehicle).

This supply convoy will execute the following actions:

- Exit the CSC to travel (in formation) to theater base (east of Port of Topo).
- Upload supplies and then travel eastward to coordinate at the CSC.
- Exit the CSC and continue eastward toward the distribution hub at Lochini.
- Unload transported supplies at the distribution hub and then return to the CSC.

Once the required supplies have been unloaded at the Lochini hub, they will be transported first to the TSB(D) and from there to the customer unit within the 1st Cav Div.

4.2 Vignette Simulation Using an Agent-Based Model

In this section, the results of simulating the EBAL vignette (as discussed in section 4.1) using an ABMS software package are presented and discussed.

Within the context of an ABMS software package, an agent is an autonomous software entity that interacts with its environment according to its own active properties or preferences and goals (figure 14). Such an agent is represented by both dynamic variables indicating its state and rule-based actions and activities indicating its behavior. Such an agent can also socially interact with other agents via the exchange of messages and has the ability to adapt and learn from its experiences (Maes, 1990). Finally, a simulation agent is a software agent that represents a "real-world" physical entity (e.g., a platform, a human Soldier) as instantiated within a simulated world. It typically does not interact with human users (although it can within the context of participatory simulations).

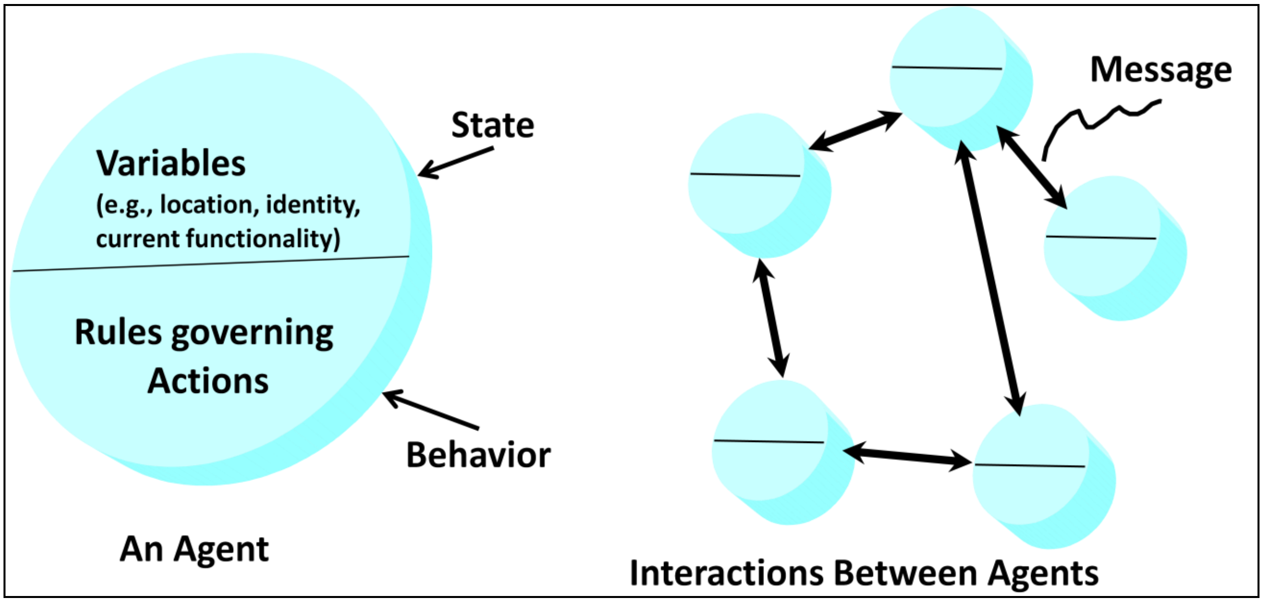

Figure 14. Illustrative description of a generic software agent.

For the purpose of demonstrating a simulation of the EBAL vignette, we used a generic ABMS software platform, wherein all agent activities and behaviors were scripted according to the vignette. As part of the demonstration, we designed a set of four performance measures to quantify the operational readiness of both the supply convoy (the provider of required materiel) and the higher priority unit within 1st Cav Div (the customer of that materiel) as defined according to the EBAL vignette.

1. Convoy Readiness to Provide Class III Supplies: The fraction of convoy vehicles functionally equipped and ready to transport class III supplies as a function of time. This is mathematically represented as

$$CR_{Class\ III}(t) = \frac{\sum_{n=1}^{3} R_{Class\ III}^{truck\ n}(t)}{3}, \tag{1}$$

where

$CR_{Class\ III}\ (t)$ = total convoy readiness to provide class III supplies as a function of simulation time t, and

$R_{Class\ III}^{truck\ n}(t)$ = task readiness of convoy truck n to provide class III supplies as a function of simulation time t, where

$$R_{Class\ III}^{truck\ n}(t) = \begin{cases} 1 \text{ when truck } n \text{ has sufficient capabilities to execute its transport task} \\ 0 \text{ otherwise} \end{cases}.$$

2. Convoy Readiness to Provide Class V Supplies: The fraction of convoy vehicles functionally equipped and ready to transport class V supplies as a function of time. This is mathematically represented as

$$CR_{Class\,V}(t) = \frac{\sum_{n=4}^{5} R_{Class\,V}^{truck\,n}(t)}{2}\,, \tag{2}$$

where

$CR_{Class\,V}\,(t)$ = total convoy readiness to provide class V supplies as a function of simulation time t, and

$R_{Class\,V}^{truck\,n}(t)$ = task readiness of convoy truck n to provide class V supplies as a function of simulation time t, where

$$R_{Class\,V}^{truck\,n}(t) = \begin{cases} 1 \text{ when truck } n \text{ has sufficient capabilities to execute its transport task} \\ 0 \text{ otherwise} \end{cases}.$$

3. Convoy Readiness to Provide Class VII Supplies: The fraction of convoy vehicles functionally equipped and ready to transport class VII supplies as a function of time. This is mathematically represented as

$$CR_{Class\,VII}(t) = R_{Class\,VII}^{truck\,6}(t)\,, \tag{3}$$

where

$CR_{Class\,VII}\,(t)$ = total convoy readiness to provide class VII supplies as a function of simulation time t, and

$R_{Class\,VII}^{truck\,6}(t)$ = task readiness of convoy truck 6 to provide class VII supplies as a function of simulation time t, where

$$R_{Class\,III}^{truck\,6}(t) = \begin{cases} 1 \text{ when truck 6 has sufficient capabilities to execute its transport task} \\ 0 \text{ otherwise} \end{cases}.$$

4. 1st Cav Div Operational Readiness: The fraction of platforms within the 1st Cav Div functionally equipped and ready to execute their assigned mission tasks as a function of time. This is mathematically represented as

$$DR_{Mission\,Tasks}(t) = \frac{\sum_{m=1}^{1000} R_{Mission\,Tasks}^{platform\,m}(t)}{1000}\,, \tag{4}$$

where

$DR_{Mission\,Tasks}\,(t)$ = total division level operational readiness of materiel systems to execute assigned mission-supporting tasks as a function of simulation time t, and

$R_{Mission\,Tasks}^{platform\,m}(t)$ = task readiness of platform m to execute assigned mission-supporting tasks as a function of simulation time t, where

$$R_{Mission\,Tasks}^{platform\,m}(t) \begin{cases} 1 \text{ when platform } m \text{ has sufficient capabilities to execute } all \text{ assigned tasks} \\ 0 \text{ otherwise} \end{cases}.$$

For the purposes of this demonstration, we have notionally assumed that 1st Cav Div is at full combat strength when 1000 platforms within the division are fully capable of executing assigned mission tasks.

Each performance measure is updated and recorded at the same sampling frequency throughout a simulation run of the ABMS demonstration.

To support the calculation of the supply convoy and 1st Cav Div performance metrics, we use the System Capabilities Analytic Process (SCAP) as developed by Agan (figure 15). Basically, SCAP allows the system analyst to define an explicit and quantitative relationship between the components making up a system and the resultant capabilities produced by the system. Agan relates the process illustrated in figure 15 to a system's constituent materiel/personnel and the necessary actions related to executing a mission task via the following mnemonic: "When components are grouped into sub-systems, they will produce functions that will provide the capability to complete the mission task" (Agan, 2010). Upon inspection, it is straightforward to map the elements making up the SCAP abstraction into MMF levels 2, 3, and 4. For a more detailed description of SCAP and its application to the analysis of the ABMS demonstration performance metrics using component, subsystem, and capability states, the reader is referred to appendix A.

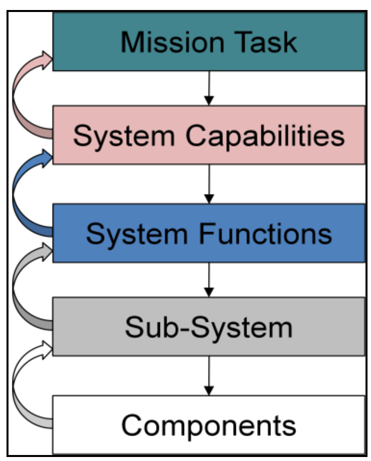

Figure 15. Diagram of the SCAP as developed by Agan.

Figure 16 illustrates the initial state of the ABMS vignette simulation. Note that all Blue force simulation agents are visually represented as small blue squares (several of which will move across the terrain map as a function of mission time). This figure identifies all of the important Blue force operational landmarks relative to the terrain map window within the ABMS, including the sea ports of Topo and Tatumi on the western coastline of the nation of Ageori, the Logistics Theater Base to the east of Topo, the APOD at Tenaki, the Convoy Support Center near the center of Ageori, the distribution hub and APOD at Lochini, the TSB to the southeast of

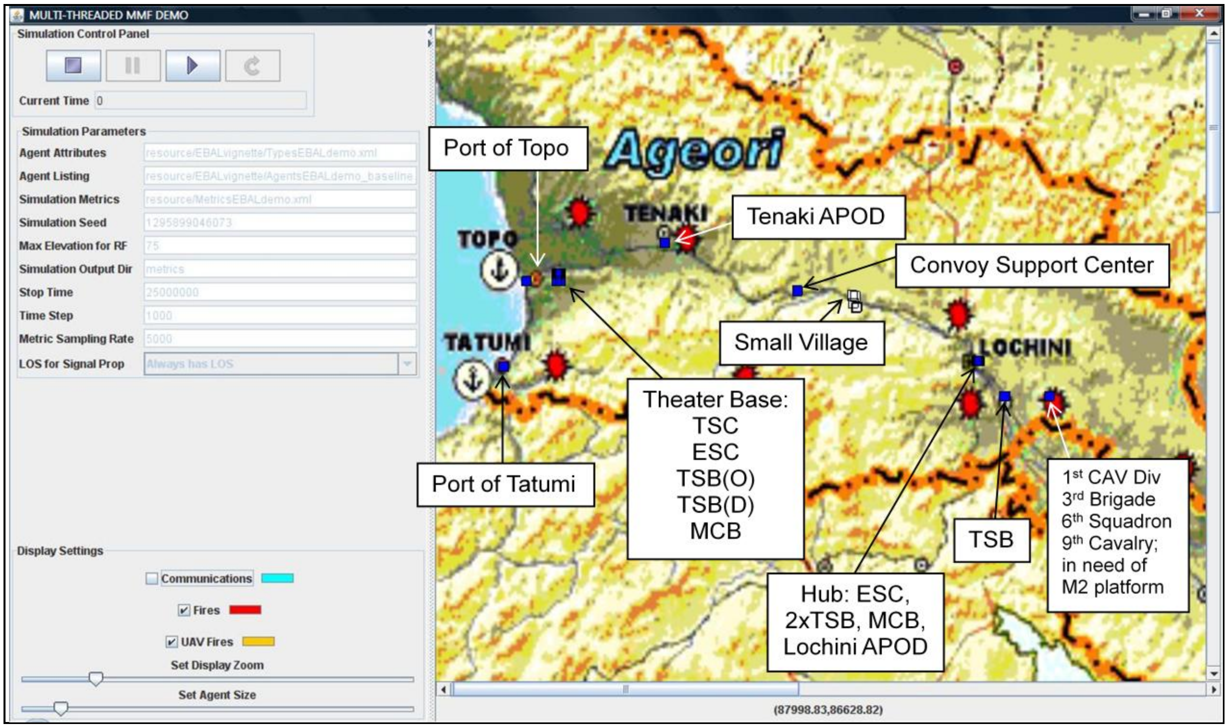

Figure 16. Initial state of the ABMS vignette simulation.

Lochini, and finally the 1st Cav Div awaiting supplies. Once the simulation commences (via a mouse-click on the triangular “play” button in the Simulation Control Panel located in the upper-left corner of the ABMS graphical user interface [GUI]), all agent activities will proceed according to the scripted sequence of events as described in the EBAL vignette (section 4.1).

Next, figure 17 illustrates the onset of the EBAL vignette simulation after 33 min (in real time) have elapsed. Here, the USNS *Benavidez* (loaded with a Bradley M2 vehicle) approaches the Port of Topo. At the same time, the supply convoy leaves the CSC and moves out toward the theater base (where the convoy plans to upload fuel, ammunition, and a Bradley M2, all of which are needed by 1st Cav Div). Associated with this simulation state, figure 18 presents time series graphs of the four task readiness performance measures associated with the supply convoy and 1st Cav Div, where the horizontal axis should be read as elapsed mission time (in units of 10^7 cs). The three task readiness metrics associated with the simulated supply convoy (i.e., Provide Class III Supplies, Provide Class V Supplies, and Provide Class VII Supplies) start out at a level of 1.0, indicating full functional readiness by the convoy to execute these tasks. Also note that the operational readiness of 1st Cav Div (the “customer” unit in this scenario) starts out at a level of 0.85 (indicating that 850 of the 1000 platforms in the division possess sufficient available capabilities to execute all mission-oriented tasks as have been assigned per platform), which is below the 90%-or-better level required by G-3. Finally, the ABMS GUI displayed in figure 19 identifies all of the radio-based communication channels connecting Blue simulation agents at t = 33 min using light blue lines.

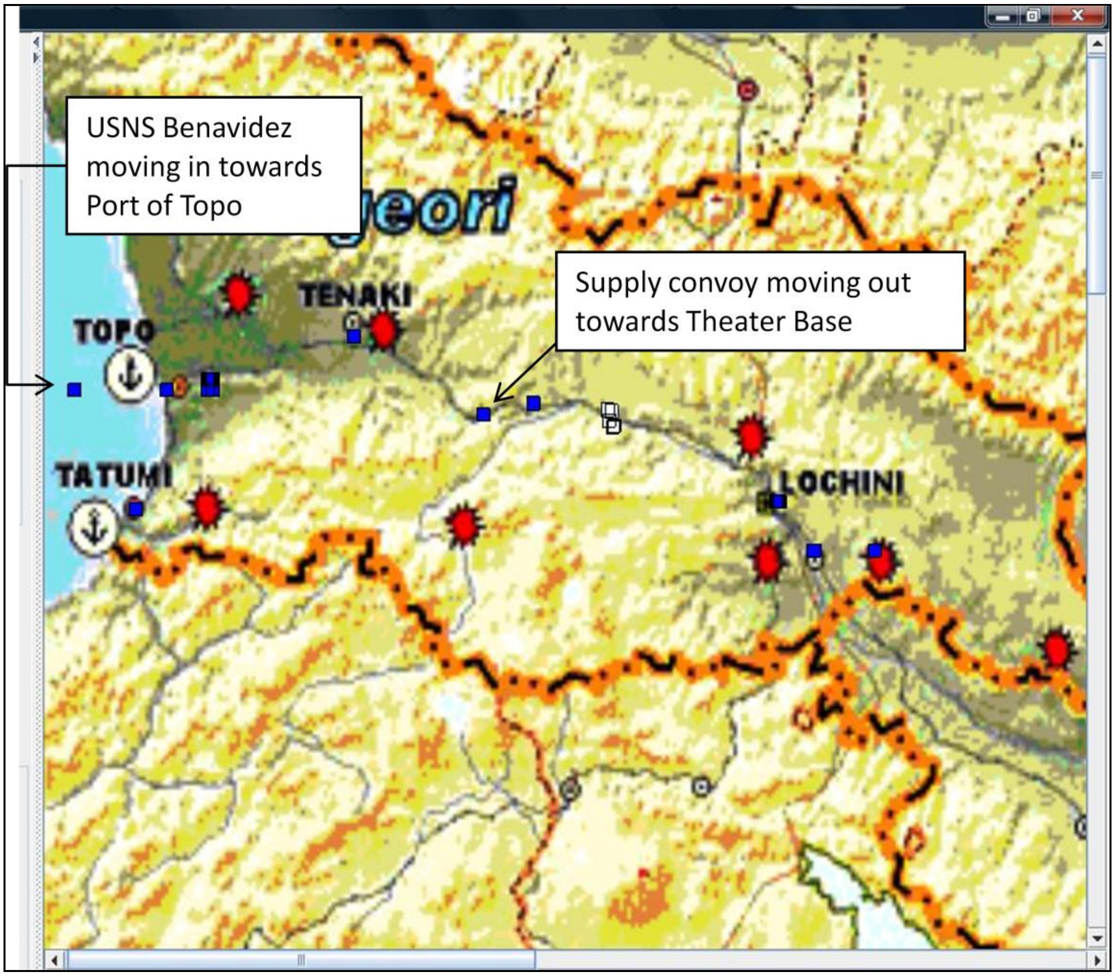

Figure 17. ABMS simulation state after 33 min has elapsed.

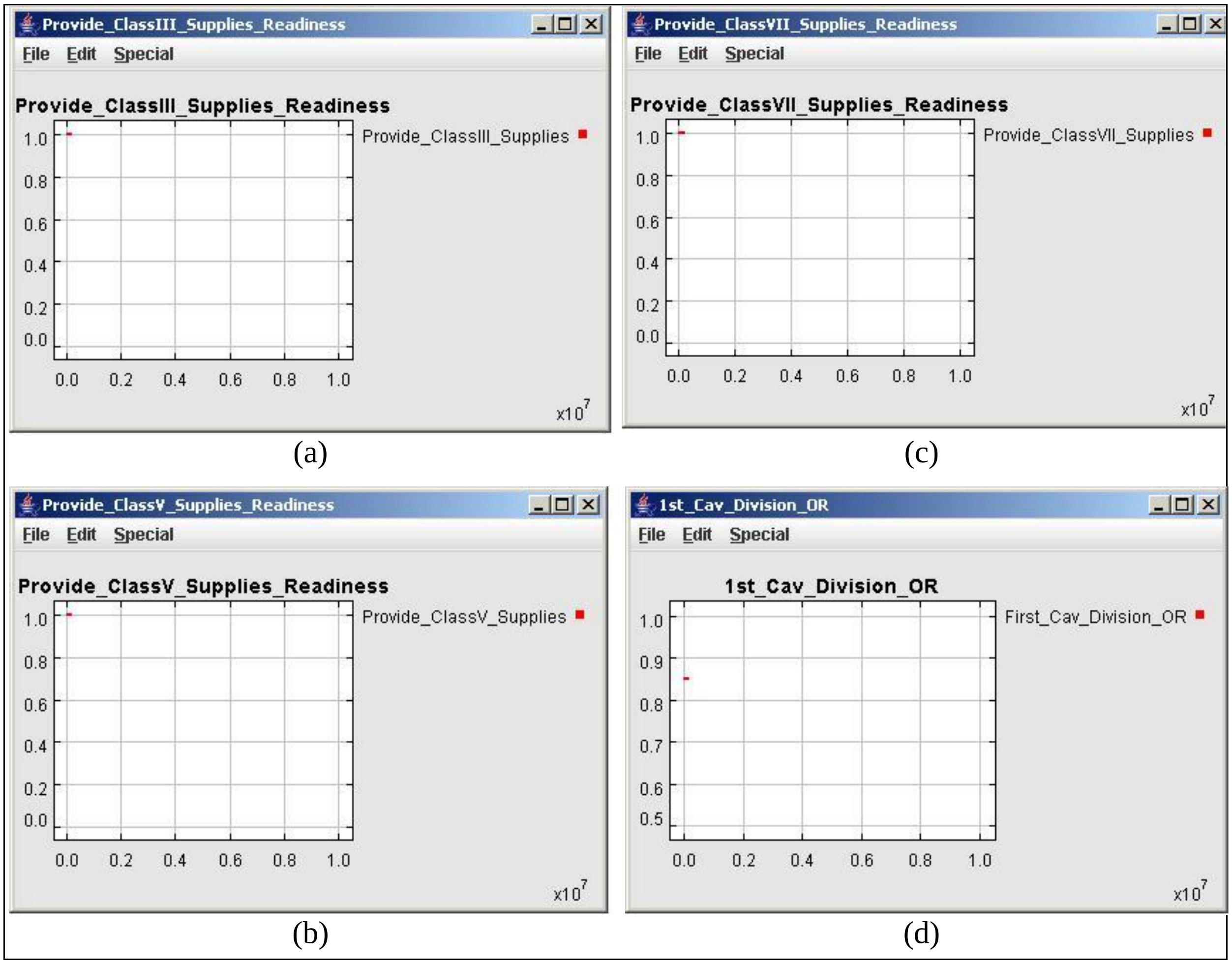

Figure 18. Time series graphs of the four task readiness measures within the simulation after 33 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

Figure 19. State of the Blue force communication network after 33 min have elapsed, where aqua-colored lines represent duplex communication channels between pairs of agents.

After this, the next significant event within the demonstration simulation occurs after 91 min (in real time) have elapsed. This situation is displayed in figure 20. At this point in time, the USNS *Benavidez* has docked at the Port of Topo and is ready to offload its cargo. At the same time, the supply convoy continues to move toward the theater base east of Topo. Meanwhile, the performance measure states shown in the associated time series graphs (figure 21) indicate that both supply convoy and 1st Cav Div task readiness levels remain unchanged as the resupply mission progresses through time.

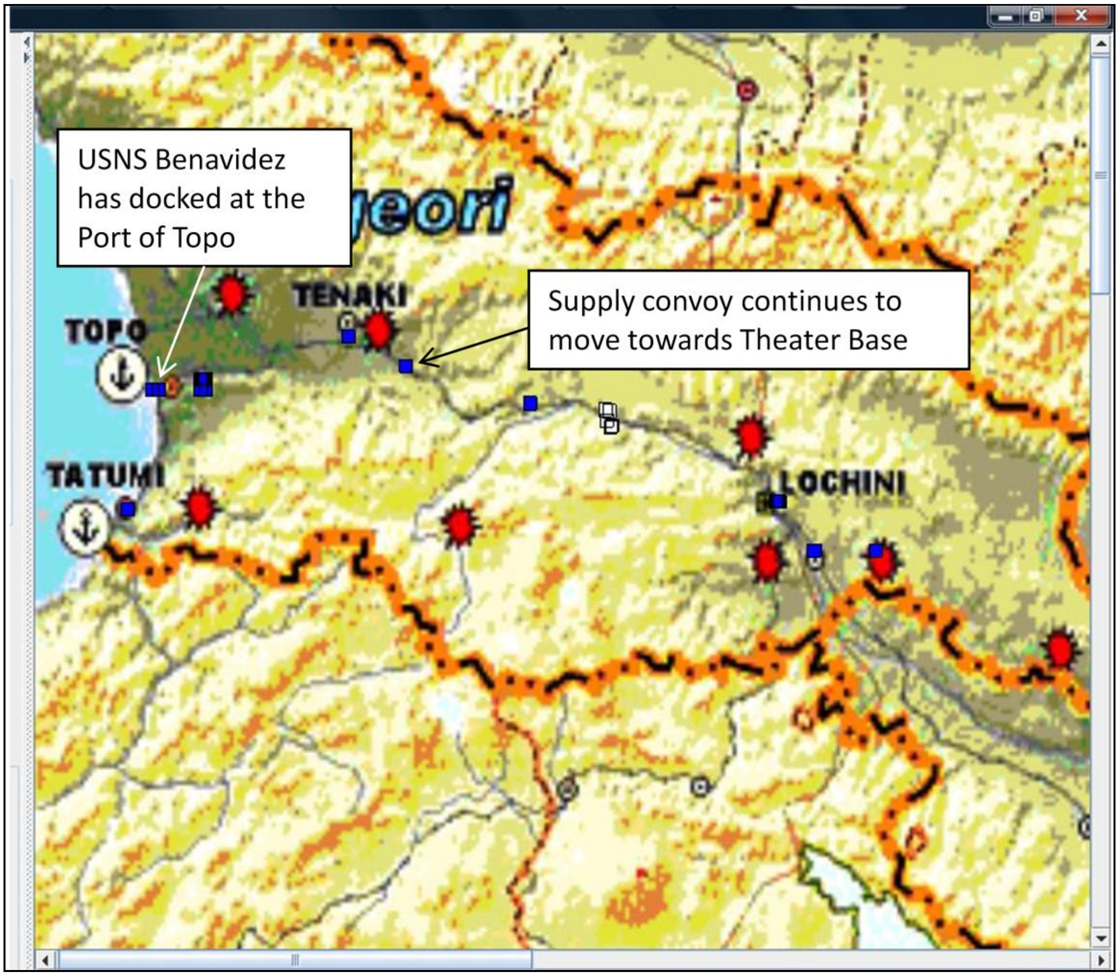

Figure 20. ABMS simulation state after 91 min have elapsed.

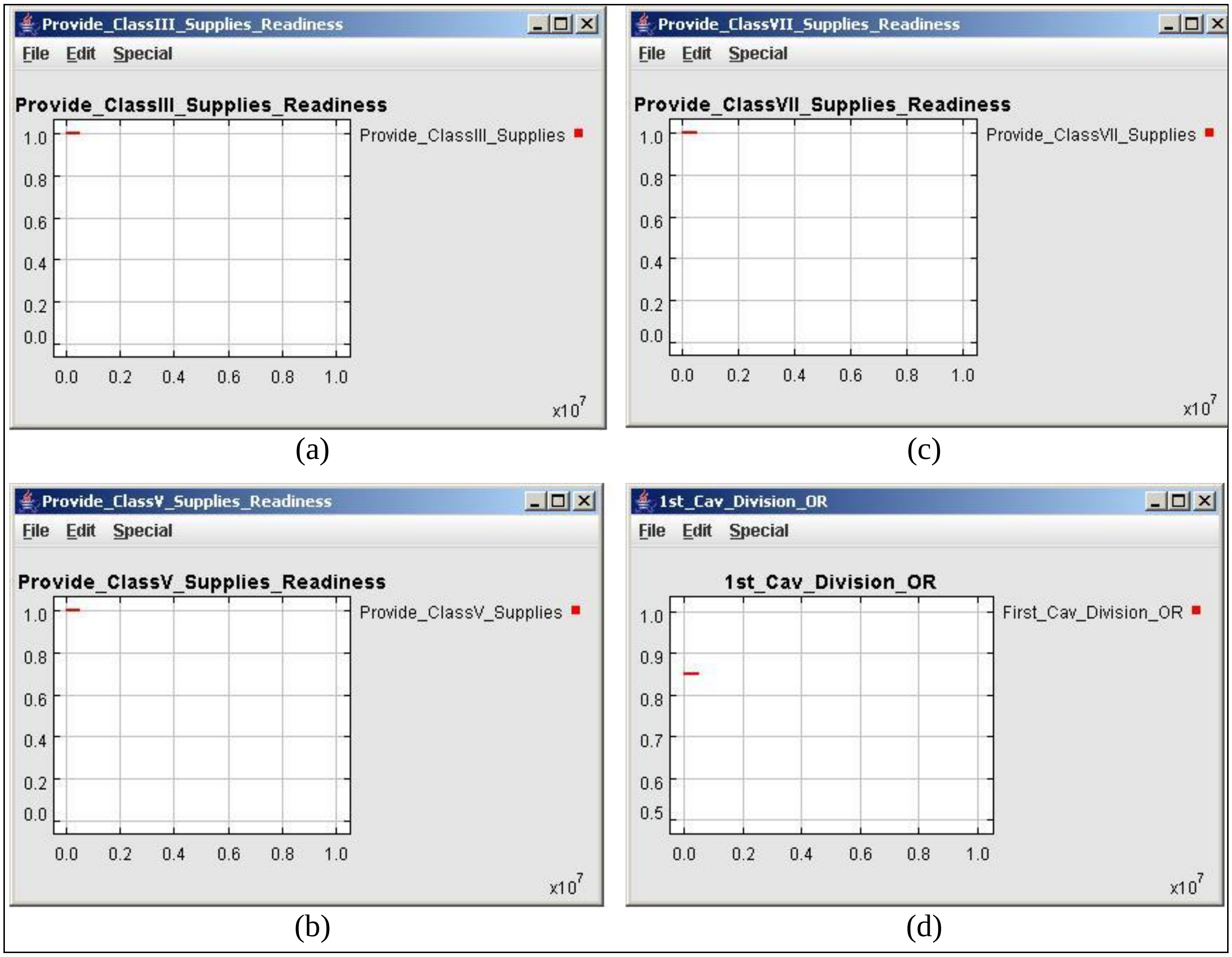

Figure 21. Time series graphs of the four task readiness measures within the simulation after 91 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

Now, after 8 h and 2 min of mission time have elapsed, the next significant state of the simulation is presented in figure 22. By this point in time, the Bradley M2 has been offloaded from the USNS *Benavidez* at the Port of Topo and is undergoing transport to theater base, while (at the same time) the supply convoy goes through check-in procedures at theater base. And, as was the situation during the last simulation update, the associated performance measure states displayed in figure 23 again indicate that all task readiness levels continue to remain unchanged.

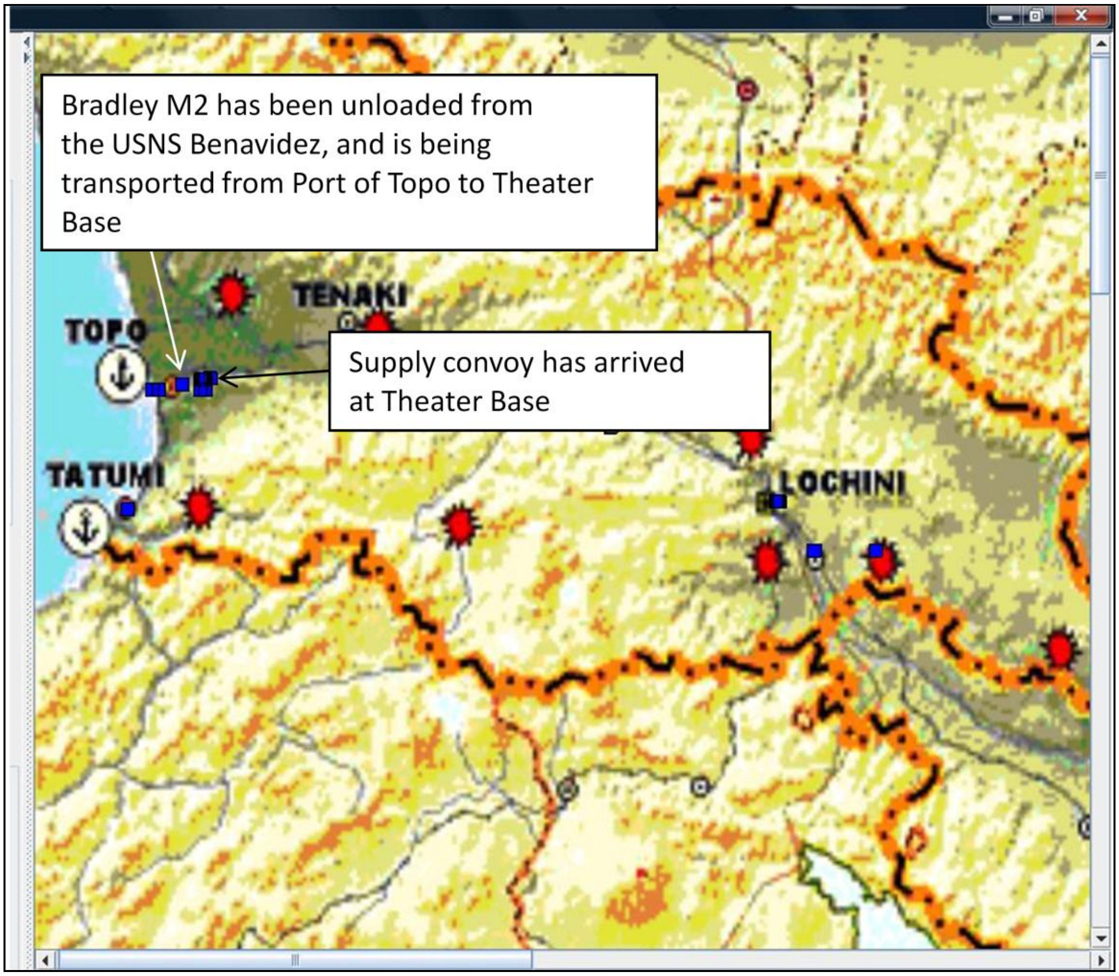

Figure 22. ABMS simulation state after 482 min (i.e., 8 h and 2 min) have elapsed.

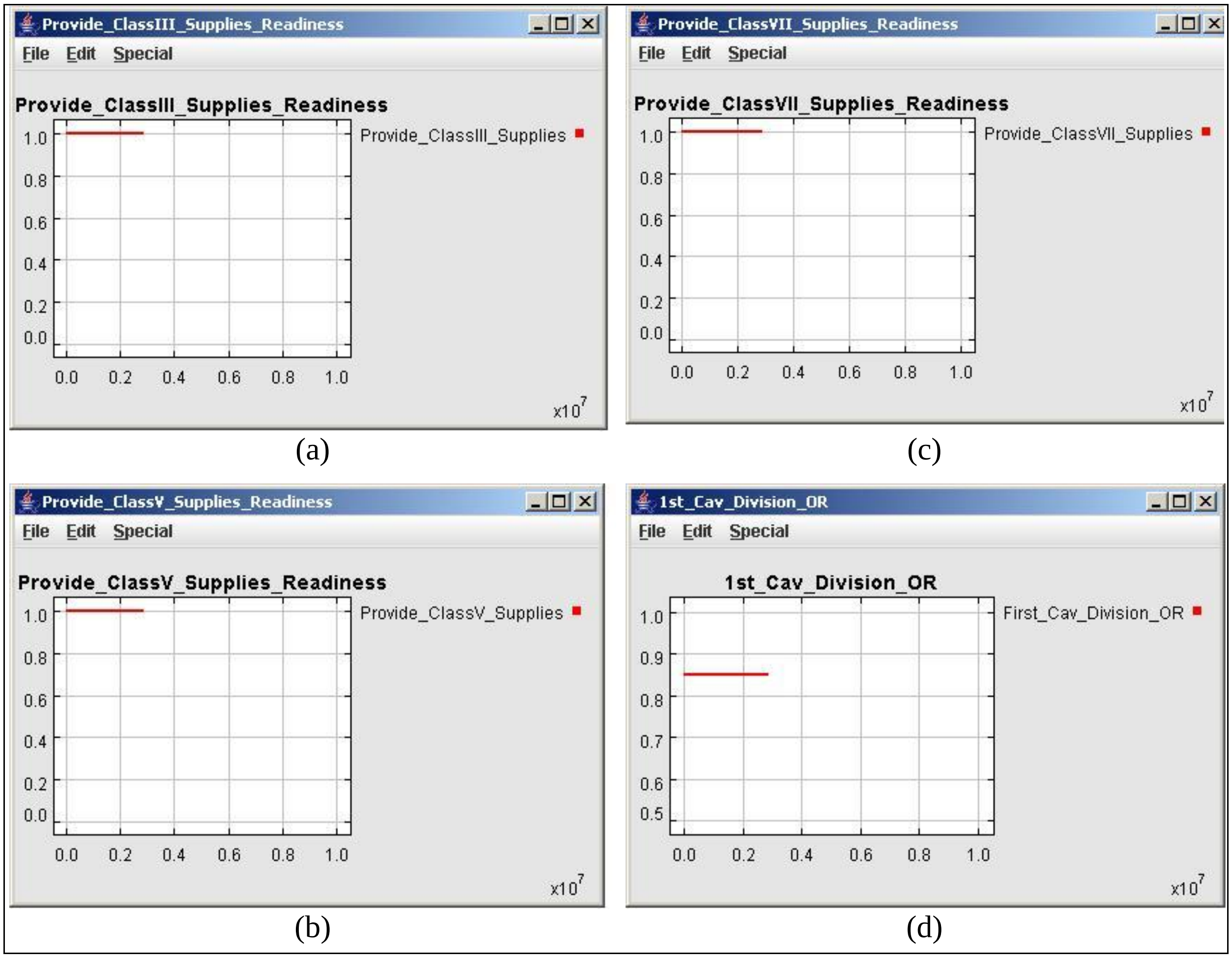

Figure 23. Time series graphs of the four task readiness measures within the simulation after 482 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

Next, the state of the EBAL vignette simulation after 17 h and 3 min have elapsed is depicted in figure 24. By this point in time, all required supplies (including the Bradley M2) have been uploaded to the supply convoy at theater base, and the supply convoy has already checked in and departed the CSC and is now currently moving onward toward a small village. Since we now assume that G-2 (i.e., the Blue force military intelligence domain) has previously indicated the possible presence of anti-American extremist activity within this village, the supply convoy commander must now be on the lookout for suspicious activity indicating the possible presence of enemy IEDs. As was the situation before, the four performance measures displayed in figure 25 indicate that all task readiness levels continue to remain unchanged.

Figure 24. ABMS simulation state after 1023 min (i.e., 17 h and 3 min) have elapsed.

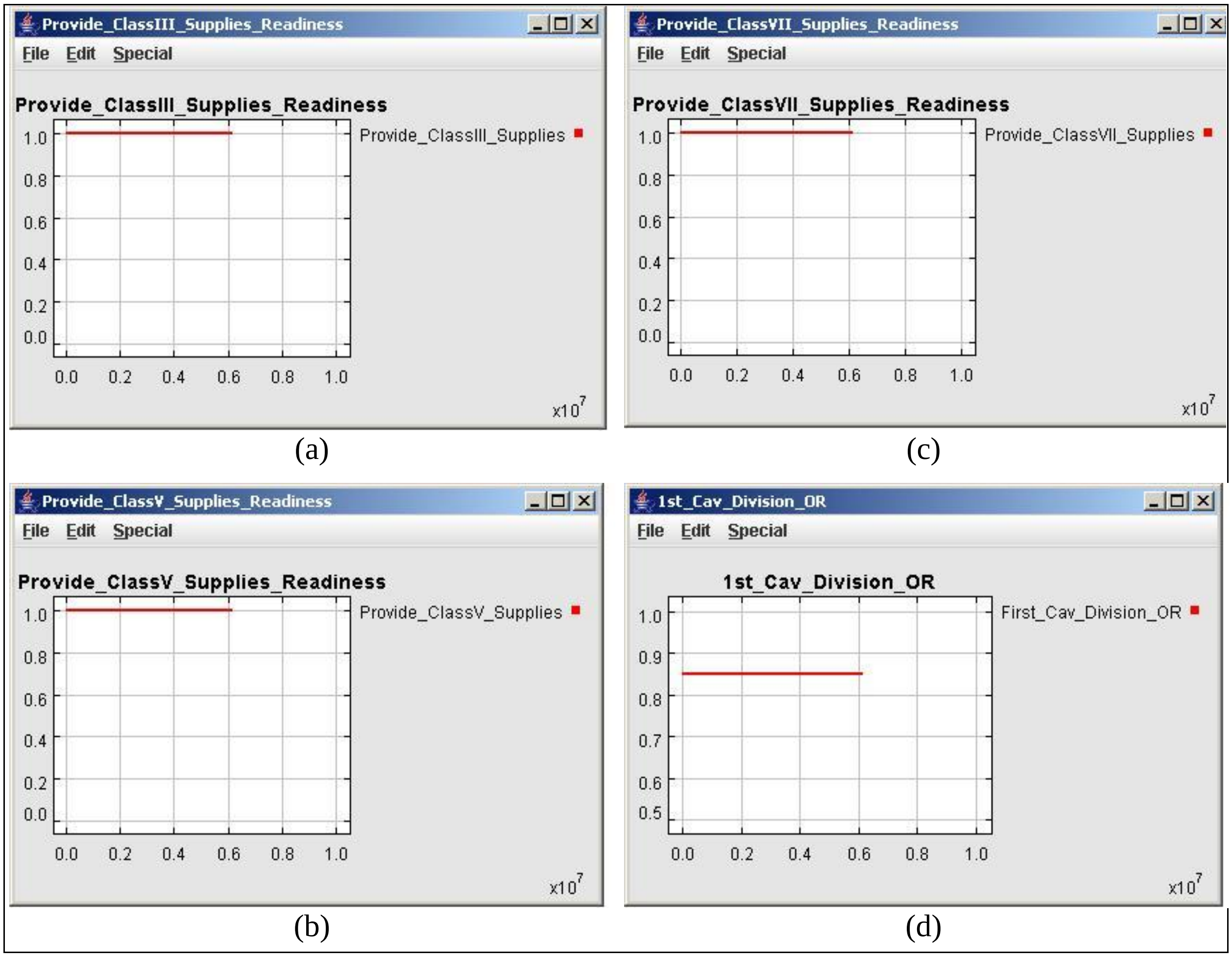

Figure 25. Time series graphs of the four task readiness measures within the simulation after 1023 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

At this point in the demonstration, in order to clearly illustrate the value of applying the multithreaded MMF to an operational context, we will engage in a "what if?" analytic exercise by considering the possible occurrence of two different subsequent measurable situations:

- Situation no. 1: The Blue supply convoy *will not* be intercepted by IEDs planted by hostiles.

- Situation no. 2: The Blue supply convoy *will definitely* be intercepted by hostiles with planted IEDs.

We further assume that either situation can manifest itself with equal likelihood (i.e., 0.5 probability of occurrence) within a simulation instance of the demonstration vignette as the result of a random draw. The following two subsections will demonstrate the simulation results from both situation types.

4.2.1 Blue Supply Convoy Situation No. 1

In the first situation, the Blue supply convoy manages to safely pass through the aforementioned small Ageorian village without incident and then continues on its way toward the Blue force logistics distribution hub at Lochini. Figure 26 illustrates the state of the demonstration vignette simulation after 18 h and 4 min have elapsed. As is represented by the blue agent marker in the ABMS GUI, all trucks within the supply convoy retain full materiel/personnel functionality and capability, so that all may continue to execute their respective supply transportation tasks. Note that all task readiness performance metrics associated with the supply convoy (figure 27) continue to evolve at levels of 100% readiness. The amount of required supplies for this scenario was defined as the minimum necessary to effect changes in readiness states. This limitation was chosen to emphasize the modeling effects due to combat thread losses.

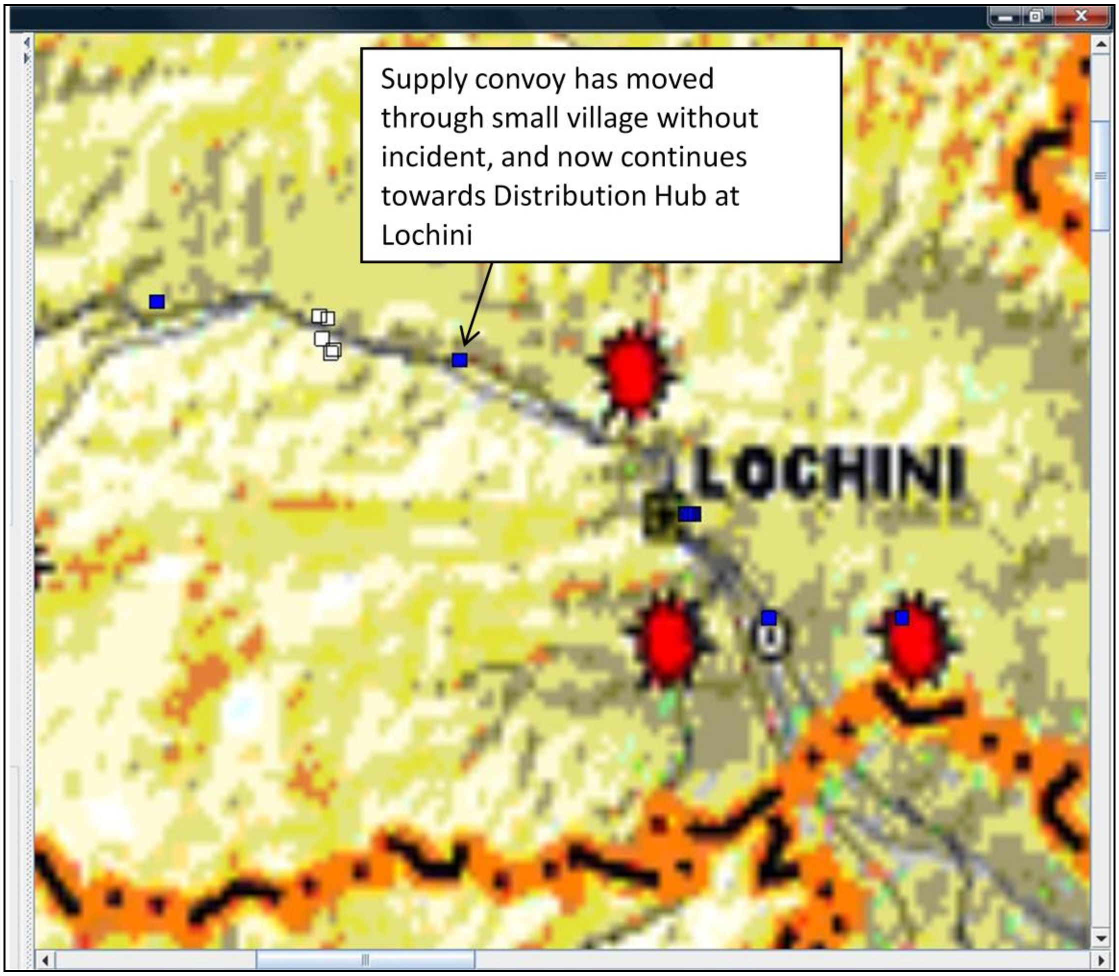

Figure 26. ABMS simulation state (assuming no interception of the Blue supply convoy by hostiles) after 1084 min (i.e., 18 h and 4 min) have elapsed.

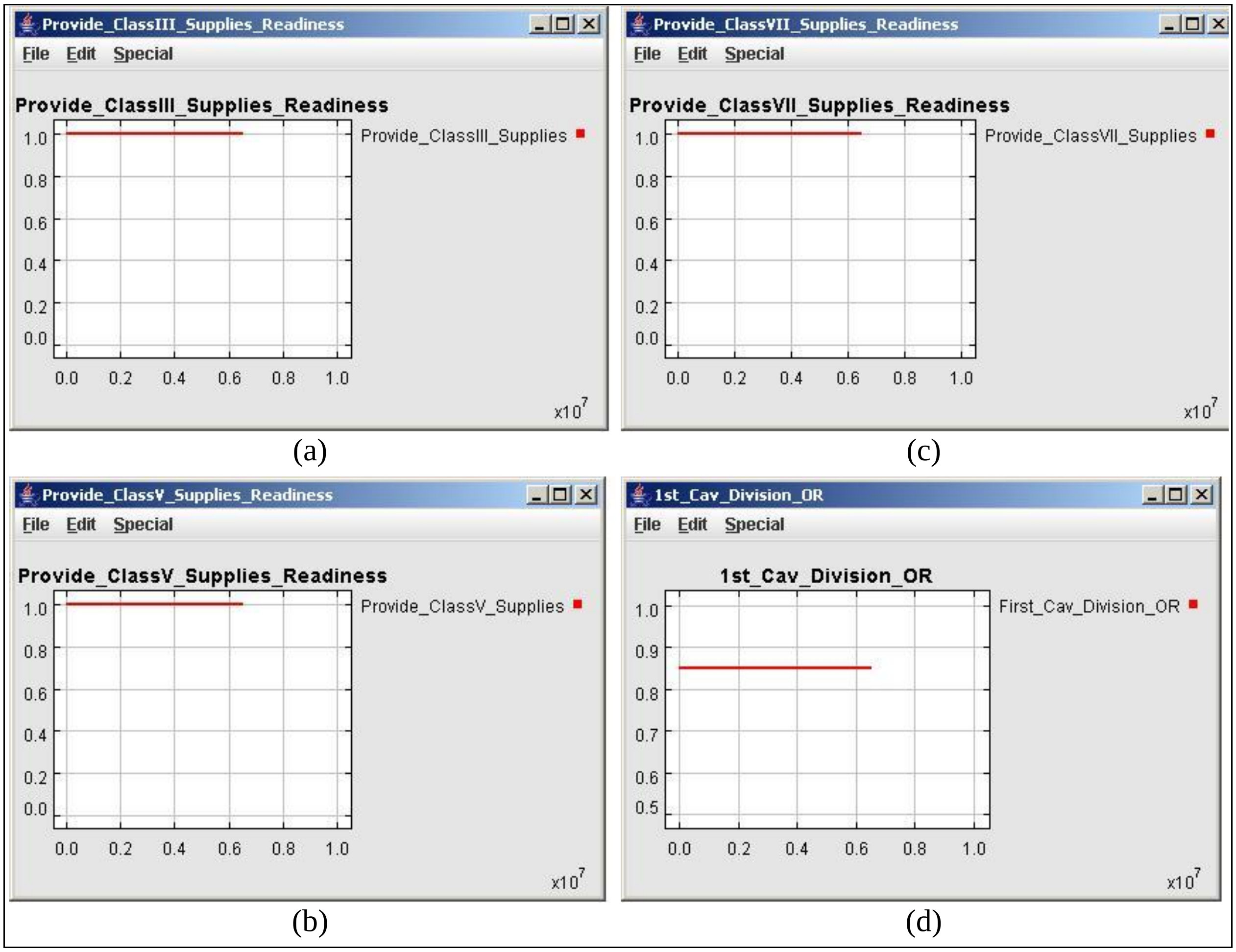

Figure 27. Time series graphs of the four task readiness measures within the simulation (assuming no interception of the Blue supply convoy by hostiles) after 1084 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

The demonstration vignette simulation concludes when the mission-prioritized customer battalion within 1st Cav Div is about to receive the much-needed fuel, ammunition, and replacement Bradley M2 from an incoming second-stage supply convoy. This final stage of the logistics operations/combat operations domain interaction within the demonstration is presented in figures 28–30. Figure 28 presents the state of the simulation after 21 h and 52 min have elapsed. Here, the supply convoy has successfully reached the Lochini distribution hub and unloaded its cargo, and is now en route back to the CSC. At the same time, a second-stage supply convoy has subsequently uploaded the original fuel and ammunition supplies plus the Bradley M2, and is thus moving onward toward the Theater Sustainment Brigade (TSB). Then, as shown in figure 29, after reaching and coordinating with the TSB following another 1 h and 49 min of additional travel time, the second-stage convey approaches the customer unit within 1st Cav Div to deliver its supplies. When the customer unit takes control of the supplies, the associated unit operational readiness level jumps up to the required value of 90% (figure 30).

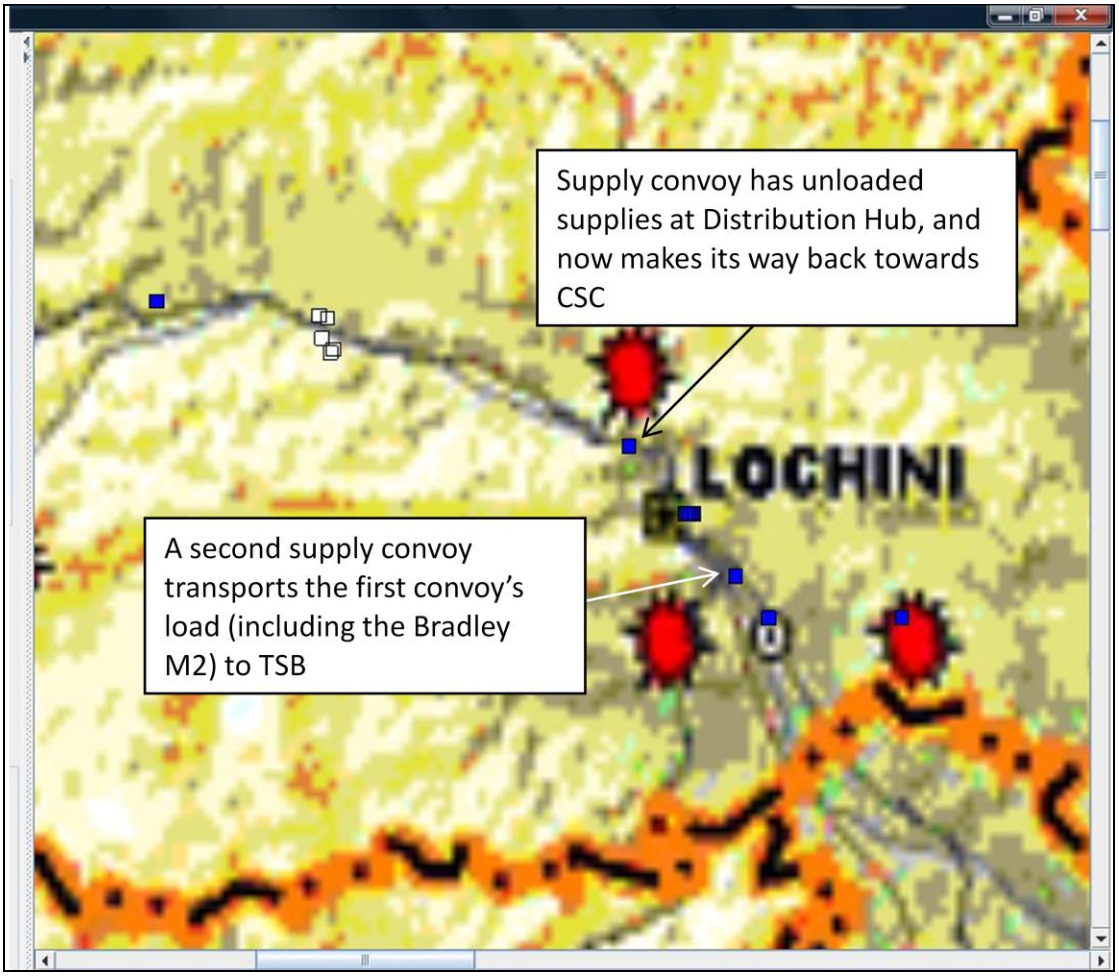

Figure 28. ABMS simulation state (assuming no interception of the Blue supply convoy by hostiles) after 1312 min (i.e., 21 h and 52 min) have elapsed.

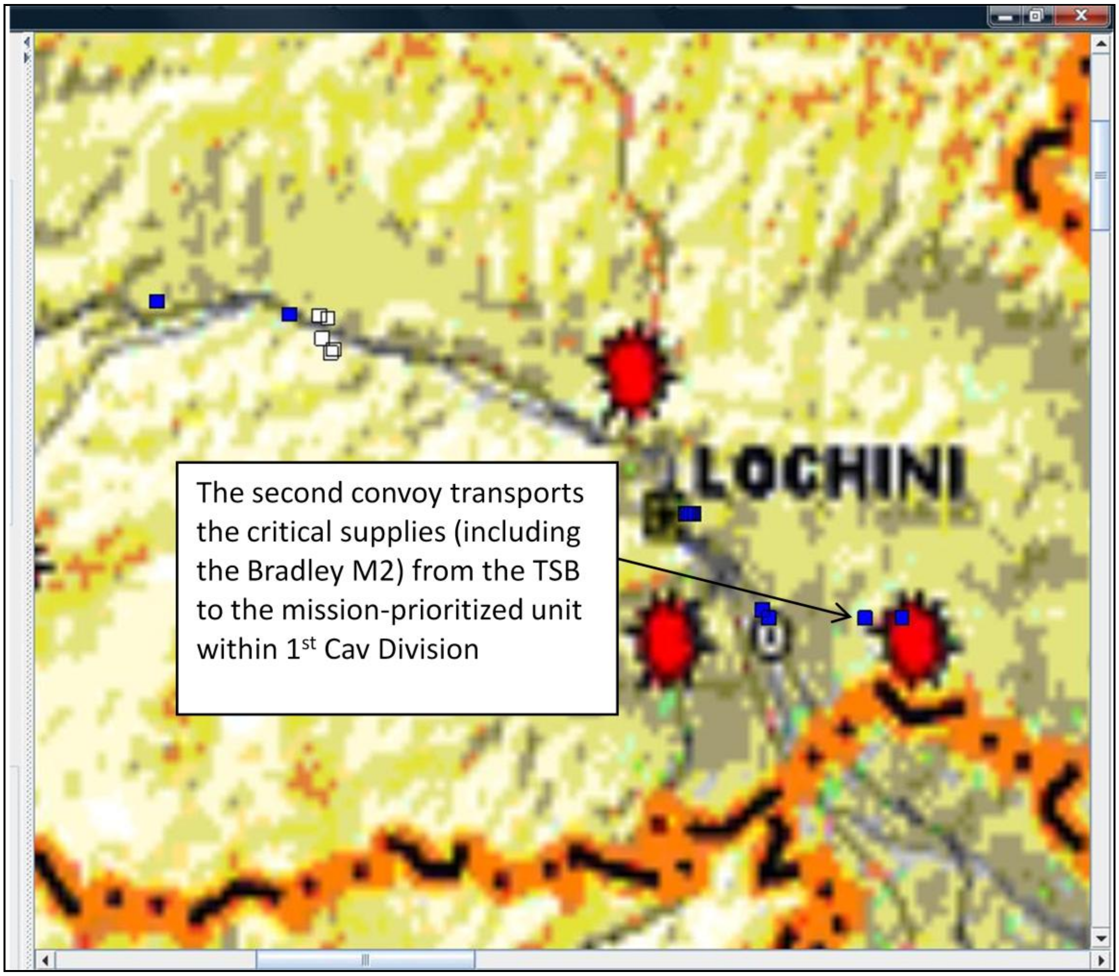

Figure 29. Final ABMS simulation state (assuming no interception of the Blue supply convoy by hostiles) after 1421 min (i.e., 23 h and 41 min) have elapsed.

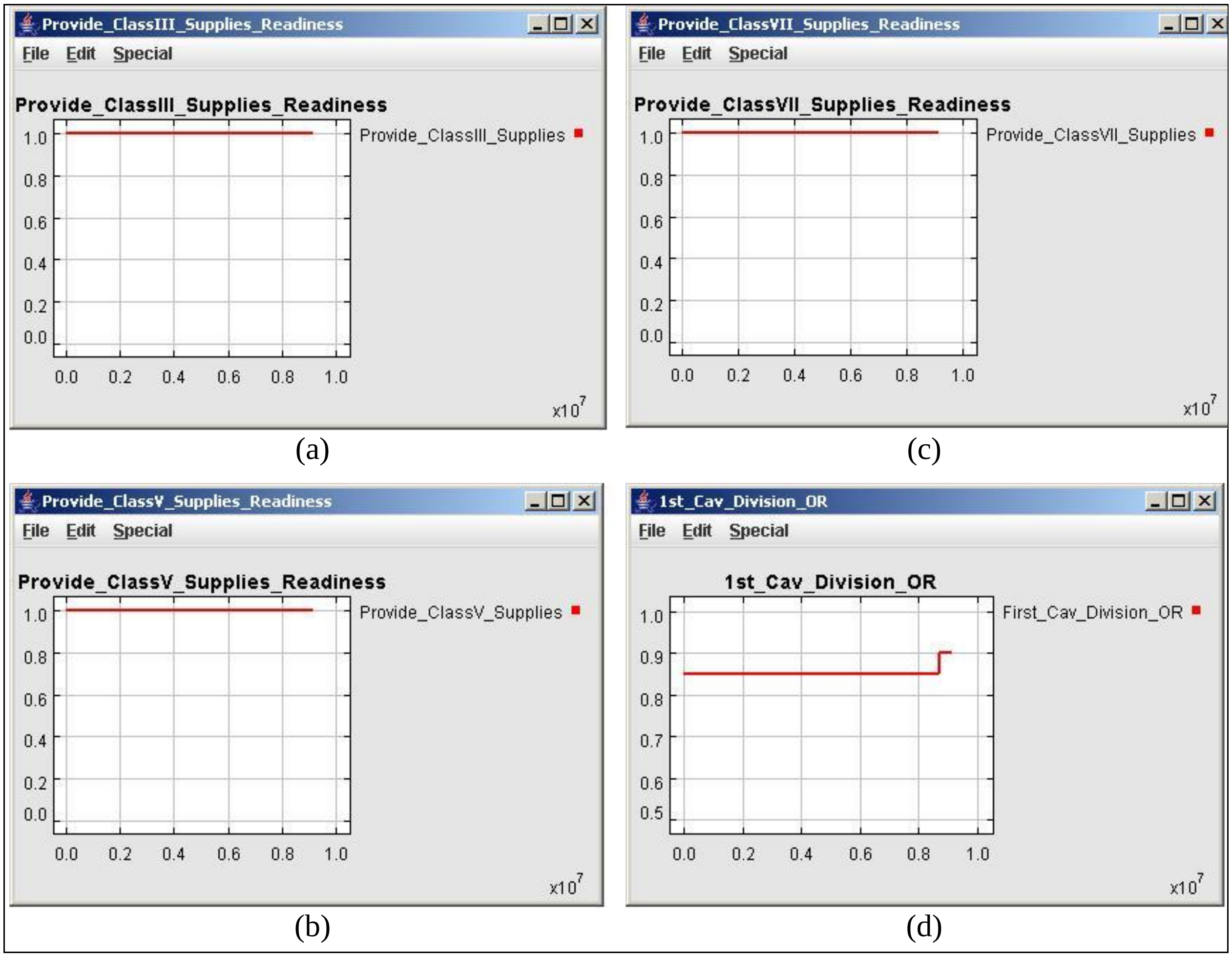

Figure 30. Time series graphs of the four task readiness measures within the simulation (assuming no interception of the Blue supply convoy by hostiles) after 1421 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

4.2.2 Blue Supply Convoy Situation No. 2

In the second situation under consideration, the Blue supply convoy is unfortunately intercepted by several IEDs planted by Janazer-inspired insurgents operating covertly within the aforementioned small Ageorian village. Figure 31 illustrates the state of the demonstration vignette simulation after 17 h and 28 min have elapsed. In this "what if?" situation, the supply convoy has been targeted and successfully attacked by a coordinated cell of anti-American extremists, where Blue platforms within the convoy that have been effectively destroyed by planted IEDs (i.e., total loss of *all* platform capabilities) are indicated by blackened agent markers. The resulting operational impact of the attack is reflected in the states of the associated task readiness performance metrics (figure 32), which serve to quantify the residual readiness of the supply convoy to deliver class III supplies (reduction to 33% task readiness), class V supplies (reduction to 50% task readiness), and class VII supplies (total loss of task readiness).

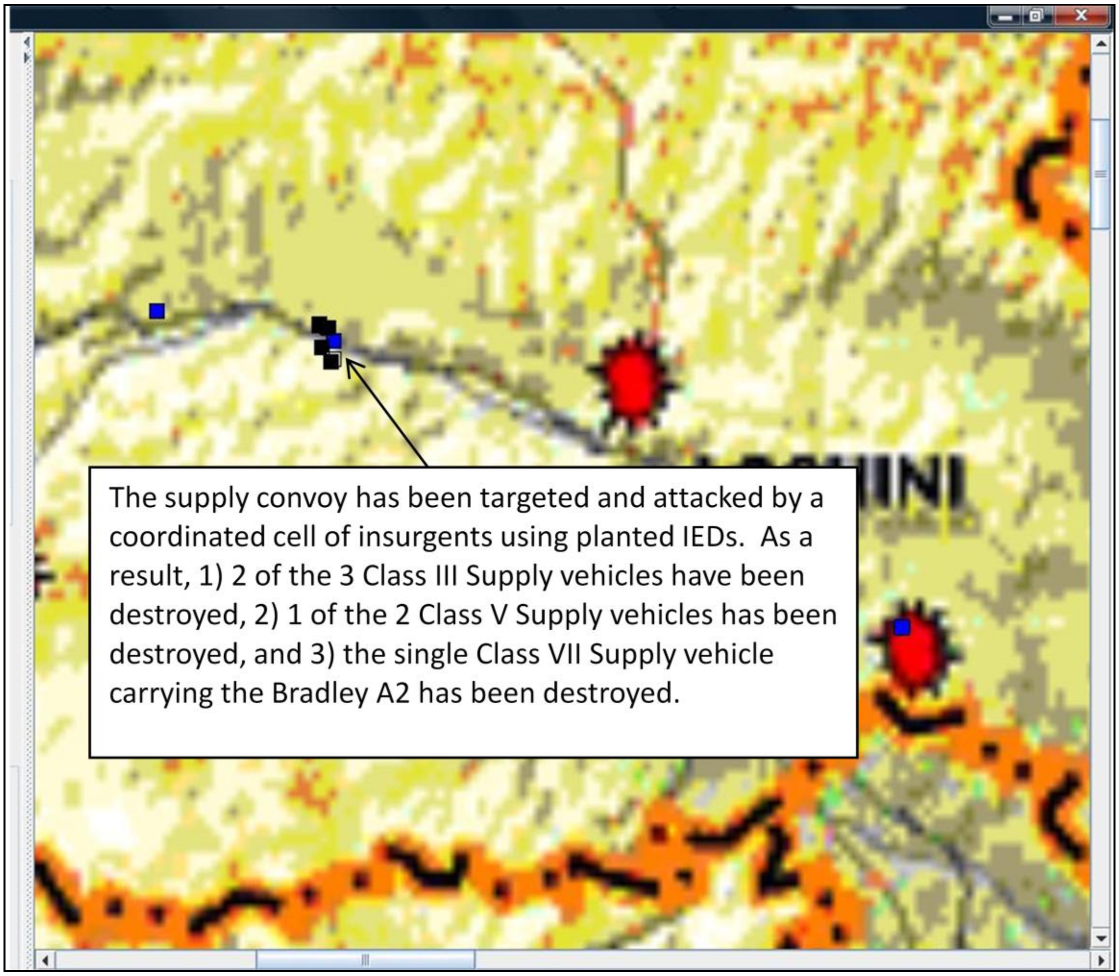

Figure 31. ABMS simulation state (assuming direct interception of the Blue supply convoy by hostiles) after 1048 min (i.e., 17 h and 28 min) have elapsed.

Finally, an assumption is made that immediately following the attack, the convoy commander will halt the supply transport operation (to assess and control the current situation and await new orders).*

To facilitate the analysis of the disruptive effects generated by the deployed IEDs upon supply convoy component, subsystem, and capability states, and the associated impact upon convoy task readiness states, the SCAP methodology is again used. For a detailed description of this SCAP-based analysis, the reader is referred to appendix B.

*The functional degradation to the supply convoy resulting from the IED attack in the demonstration vignette simulation is *purely notional* in nature and is used only for illustrative purposes. It should *not* be misconstrued to represent an actual possible situation.

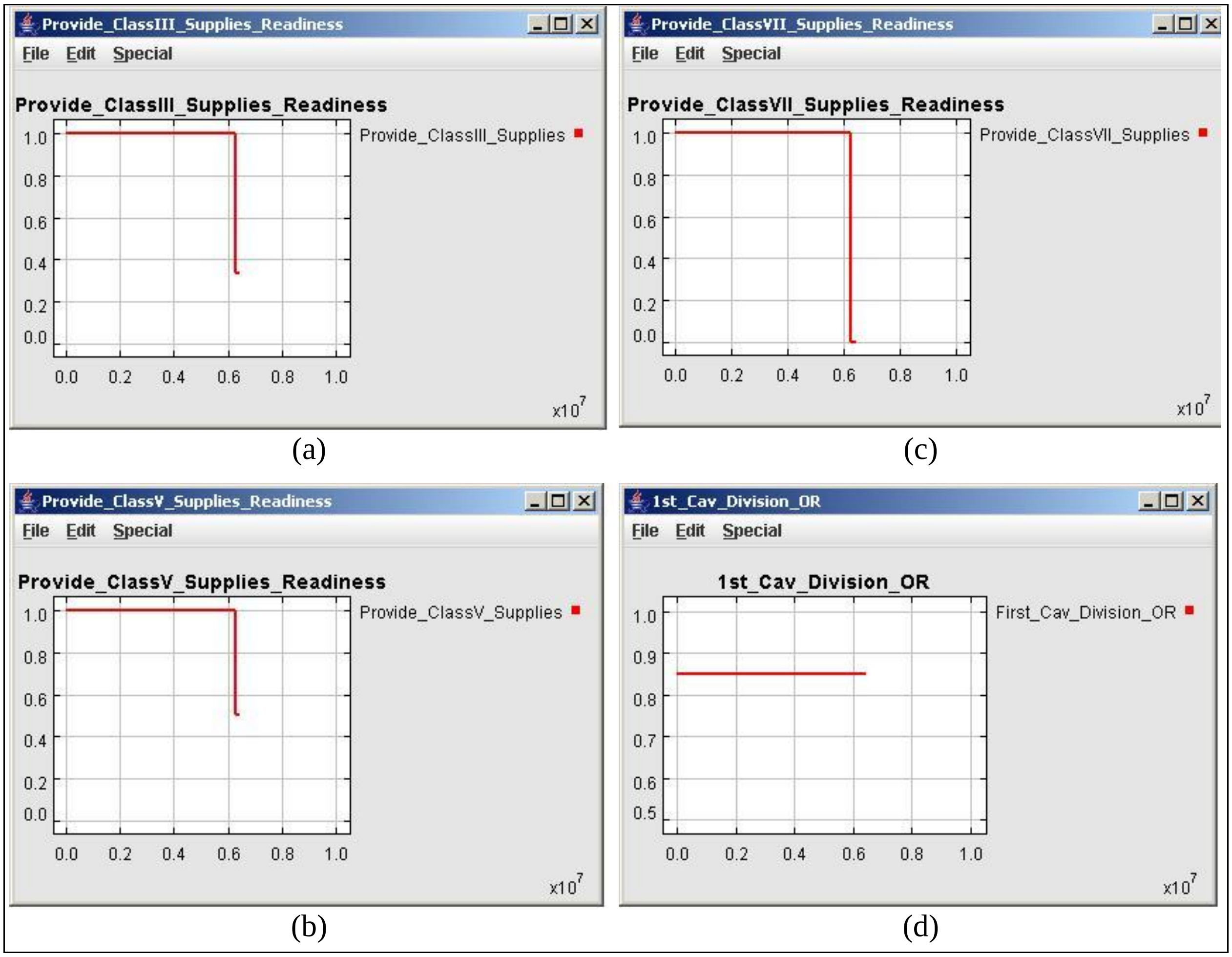

Figure 32. Time series graphs of the four task readiness measures within the simulation (assuming direct interception of the Blue supply convoy by hostiles) after 1048 min have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

This second "what if?" branch of the demonstration vignette simulation concludes after ~25 h of simulation time have elapsed (figure 33). In this alternate situation, since the supply convoy cannot continue to operate as a cohesive unit and reach the Lochini distribution hub (its next goal location within the demonstration vignette), the mission-prioritized customer battalion within 1st Cav Div *never* receives the fuel, ammunition, and replacement Bradley M2 supplies it requested. Consequently, the three task readiness performance levels for the supply convoy remain unchanged from the previous simulation update (figure 34). More importantly, the 1st Cav Div operational readiness level also remains unchanged at an unacceptable level of 85%. The reader is now encouraged to compare this result with the corresponding status in situation no. 1 (section 4.2.1), wherein the 1st Cav Div operational readiness level at a slightly earlier point in time had already increased to the mandated level of 90% because of the successful delivery of the required supplies. Thus, by using this demonstration vignette to comparatively examine the consequences of two possible situational outcomes within a Blue force logistics operations / combat operations

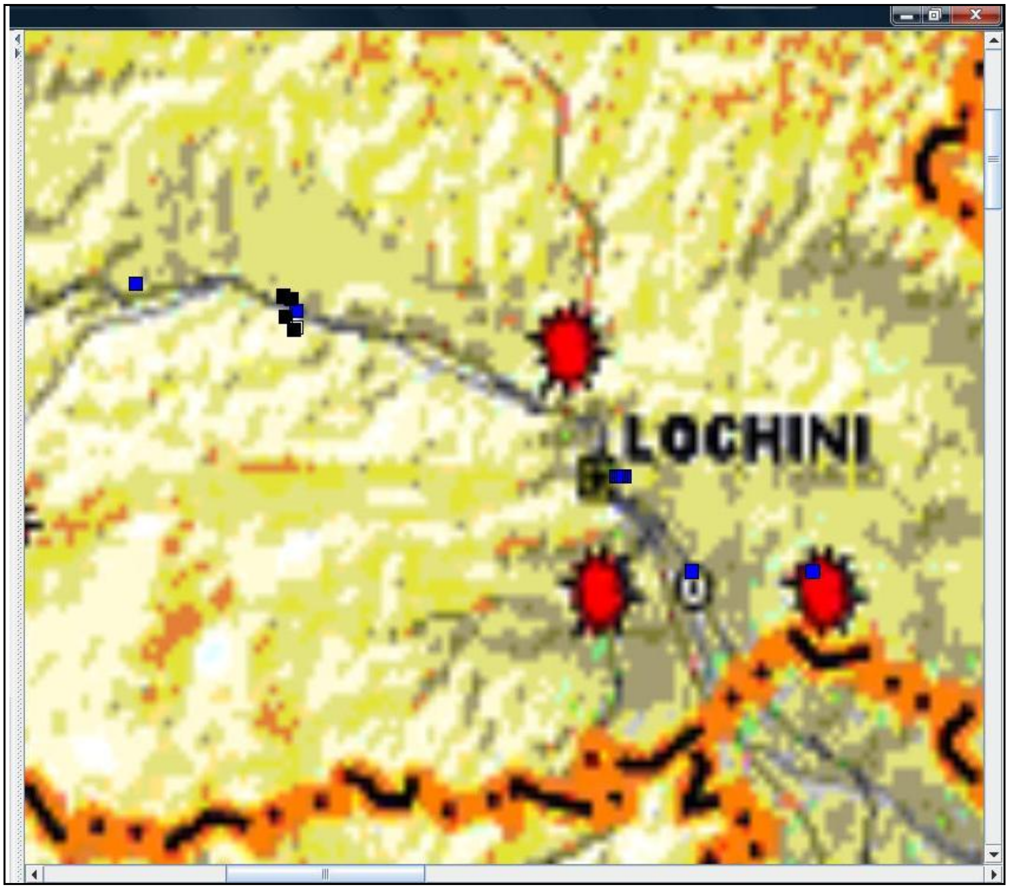

Figure 33. ABMS simulation state (assuming direct interception of the Blue supply convoy by hostiles) after ~1500 min (i.e., 25 h) have elapsed.

interaction, we have demonstrated the analytic value of the multithreaded MMF in identifying and tracking critical information elements that can provide the warfighter with an understanding of coordinated multidomain military business operations.

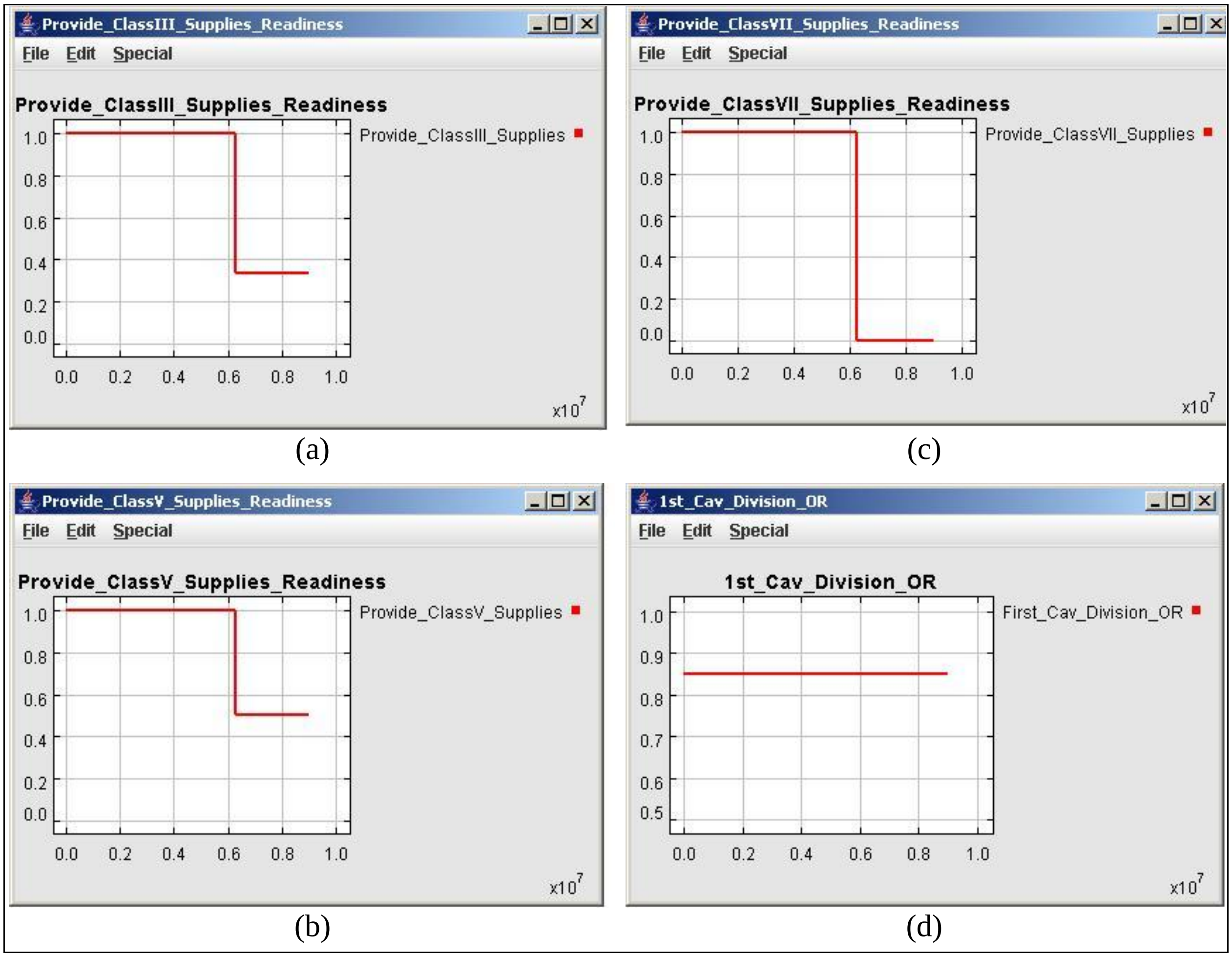

Figure 34. Time series graphs of the four task readiness measures within the simulation (assuming direct interception of the Blue supply convoy by hostiles) after ~1500 min (i.e., 25 h) have elapsed: (a) Convoy Readiness to Provide Class III Supplies; (b) Convoy Readiness to Provide Class V Supplies; (c) Convoy Readiness to Provide Class VII Supplies; and (d) 1st Cav Div Operational Readiness.

5. Discussion

The multithreaded MMF provides a means to explore the use of a modeling and simulation environment where multiple military domains or threads (e.g., logistics, transportation, combat operations, intelligence, and engineering) can be described in terms of tasking and required capabilities, and their mission interactions simulated over some mission scenario time horizon. This provides a structure that supports the extension of the original MMF from a single military thread application, combat operations, to a multithreaded MMF that can be applied to two or more operational thread interactions. Autonomous agent technology has been used to demonstrate the workings of a two-threaded MMF process that can in turn be used to study interactions that create courses of action due to changes in one or more defined state variables representing operational knowledge elements. A multithreaded MMF capability facilitates the examination of MMF level 1 battlefield interactions among two or more military threads by utilizing autonomous agent technology in a simulation environment to conduct experiments that represent military decision making with sufficient accuracy to identify those knowledge elements that are critical to taking preemptive COAs that prevent mission failure. The multithreaded MMF will provide the Army with the capability through modeling and simulation to identify knowledge and information elements that are critical to decision making that directly impact operational mission outcomes—success or failure. Knowledge and information are the key components to the human dimension side of the common operating picture. The ability to identify such knowledge elements will serve to develop advanced future force predictive analyses tools and decision-making models. This knowledge will also provide the building blocks for sustainment modeling and simulation training systems that will be needed by the future force to allow sustainment decision makers to better understand what information is critical and what the impact and ripple effects are of those decisions over mission time on overall mission success.

A military mission is multithreaded in the sense that operational, logistical, intelligence, transportation and engineering preparations and objectives are coordinated, planned for, and time phased to support the mission. This coordinated time-phased approach to the mission threads is critical to mission success. The two-threaded MMF approach described here can be extended to support the multithreaded aspects of a military mission. In addition to linking state of material to mission success for each thread, a multithreaded MMF model must link thread state objectives (tasks/capabilities/time) to mission success. In a multithreaded MMF model, MMF must have proper metrics for each thread as well as multithreaded metrics to address the threads, relationships between threads, and behaviors of entities functioning within (and across) threads.

For multithreaded analyses, traceability of interaction effects through the MMF levels provides the following:

- A predictive capability to anticipate task/capability mismatch resulting in sustainment shortfalls.
- Ability to execute multiple “what if?” scenarios to anticipate how decisions made at one level can produce a ripple effect over time and effect overall mission success.
- Better insight into cause and effect issues resulting from business process change on logistics sustainment.

The multithreaded MMF provides an ability to assess the impact of exploiting predictive knowledge and its overall impact on different aspects of mission (i.e., combat operations, logistics, transportation, engineering, intelligence) over time. In this fashion, the multithreaded MMF can serve as an exploitation and assessment tool that provides the following:

- The ability to assess the effect of logistical, transportation, engineering, and intelligence decision making on mission success as a result of exploiting predictive knowledge.
- A training assessment tool to the warfighter for insight into the cause and effects on decision making and sustainability.

The multithreaded MMF provides an opportunity to model the business process interactions that occur among decision-making entities operating in different cooperating military domains, where such business interactions are critically necessary to ensure overall mission success. When modeling such interactions within an ABMS software platform, care must be taken to represent realistic decision-making agents in all coordinated military domains, as represented by the military agent classification taxonomy shown in figure 35. Although the results of the demonstration vignette simulation presented and discussed in section 4 were intentionally constrained to interactions between OWNFOR/LOG agents, OWNFOR/OPR agents, and OPFOR agents (corresponding to Blue logistics entities, Blue combat operations entities, and Red insurgent entities, respectively), an ABMS simulation could be created wherein *all* agent types represented in the classification taxonomy engage in different interactions according to a specific mission context and situation.

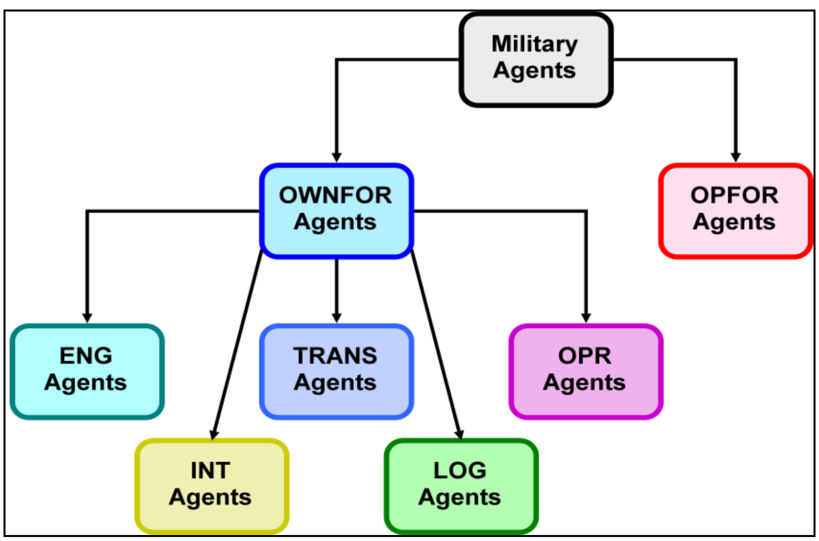

Figure 35. Classification taxonomy of military agent types.

As discussed, the multithreaded MMF was extended from the original design to support multiple interactive military threads or domains (logistics, combat operations, transportation, engineering, etc.). In a military mission, these threads interact with each other not only sequentially but often simultaneously, which is necessary to achieve the mission objective. This report provides a vignette example of how the multithreaded MMF can be instantiated in a modeling and simulation tool to explore a number of "what-if" questions related to the means for threads to operate and the impact of failure or shortcomings in the thread's means to execute on overall mission outcome (i.e., success or failure).

6. Future Efforts

A military mission represented as a complex system of systems (SoS) involves multiple threads that must successfully interact with other threads and complete their tasks for overall mission success. This also entains simulating the operations of those subordinate embedded systems, describing how those systems dynamically interact with one other, assessing the overall ability of both the SoS and subordinate systems to achieve their objectives, and assessing the impact that embedded systems (i.e., threads) failure or degradation has on overall mission success. This characterization is one way to describe a deployed military force with a mission objective. Thus, the authors believe the example vignette in this report is one application of the multithreaded MMF.

In addition, we believe that the multithreaded MMF abstraction can be applied to a diverse set of complex military problems that go beyond interacting military threads. For example, C2, a critical functional area to military operations, is getting significant attention with the migration to net-centric warfare. C2 can be viewed as a type of SoS problem domain. The overall system objective of military C2 is to establish a battlefield net-centric communications architecture that will allow data and information to flow among the various military threads. This data, either directly or indirectly through analytics, provide each military thread the information it requires to be aware of the current battlefield state supporting decision making that will impact or determine mission outcome. Net-centric C2 is thus a type of SoS. It involves many subsystems, such as transmission devices, cables, sensors, servers, and application software, to produce the information needed to support the overall system and mission, i.e., situational awareness. Multithreaded MMF is ideally suited to model this type of complex SoS and assess the viability of net-centric C2 systems, the impact situational awareness has with decision making, and the impact on mission success when components of information are lost or errant.

It is easy to see how a net-centric C2 system easily fits the definition of a complex SoS. The former consists of many components or subsystems whose purpose is to generate, route, and present information to military commanders on the state of battlefield conditions to support military decision making. It is conceptually easy to understand how degradation or failure of one or more components could impact mission success for a particular military thread, with “ripple” effects that impact other military threads and thus threaten overall mission success. The multithreaded MMF is applicable to examine complex net-centric C2 systems to better understand how the net-centric C2 “means” can impact mission success through simulation analysis, allowing the military to develop methods to mitigate those impacts.

The net-centric C2 system is a fairly straightforward example of a complex SoS and is well suited for treatment using the multithreaded MMF for SoS analysis. The authors also believe that the multithreaded MMF can be applied to more abstract SoS concepts with equal utility to the military. For example, the abstract concepts of "situational awareness" or "common operating picture" represent information that provides military commanders a view of the current state of the battle space. In a way, this concept of situational awareness is abstract in the sense that we do not have a good handle on the full set of information needed by an agent to be situationally aware. As abstract as this concept is, the authors believe that the multithreaded MMF paradigm can be applied to such abstract concepts in this way. In this case, the mission is to become fully situational aware. The means to achieve this mission objective are the various knowledge and information elements that are needed at specific times to achieve mission success. In this sense, errant or delayed information could present an errant situational view leading to decisions that affect military mission outcomes on the battlefield.

The military spends substantial time and money to identify knowledge that, if known in advance, would allow critical decisions to be made that would affect mitigating battlefield events leading to mission failure. There is an ongoing effort to develop advanced forecasting techniques to provide this knowledge to the warfighter. The authors believe that, in this context, we often do not know what to forecast or are unable to identify what information or knowledge is critical to mission outcome. We often identify such information in the aftermath of a catastrophic event or mission failure through forensic informational analysis. It is through this latter procedure that military commanders come to realize that if they knew this or that, they could have taken preemptive action to mitigate the problem. This is almost always the case, in that we learn what knowledge is critical to situational awareness that impacts mission outcome after the fact, prompting a reaction to develop analytics and/or forecasting tools to provide that knowledge.

We believe this type of abstract SoS concept lends itself to the multithreaded MMF, where the mission is "situational awareness" and the means to mission success is the "collection or set of information" that achieves this objective. In this case, an agent-based simulation analysis tool can be used to simulate commander decision making when the latter is presented various knowledge element states that represent the situational awareness mission. By simulating many decision variants of the same mission scenario (i.e., changing various information states within the simulated situation to allow the commanding autonomous agent to make mission decisions based on that information), one can examine the resultant impact those decision variants have on mission outcome. Taken to its logical conclusion, this analytic process can ultimately lead to potentially identifying what knowledge elements are critical to supporting decision making that is critical to mission success. Here, we contend that the multithreaded MMF could lead to a methodology to identify mission-critical information and data that impact mission outcome through simulation-based analysis.

In this report, we have discussed and demonstrated how extending the original MMF can address a variety of complex SoS problems, both real and abstract in nature. In conclusion, we believe that many current and future Army problems could be framed from an SoS perspective, making the multithreaded MMF ideally suited to explore potential analytic techniques to support decision making that leads to mission success.

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Appendix A. Application of the System Capabilities Analytic Process Within the Multithreaded Missions and Means Framework Demonstration

In the multithreaded Missions and Means Framework (MMF) demonstration vignette discussed in section 4, six trucks make up the Blue force supply convoy. As was previously described in section 3.1, the convoy trucks are tasked as follows.

- Three trucks are tasked to transport class III supplies (i.e., fuel supplies required for deployed Bradley M2 platforms). This set of supply vehicles includes trucks 1, 2, and 3.
- Two trucks are tasked to transport class V supplies (i.e., supplemental ammunition required by deployed Bradley M2 platforms). This set of supply vehicles includes trucks 4 and 5.
- One truck is tasked to transport class VII supplies (i.e., a replacement Bradley M2 ground vehicle). This last supply vehicle is truck 6.

For the purposes of the agent-based modeling and simulation (ABMS) demonstration, we assume that each supply vehicle has been engineered with an ability to individually demonstrate the following set of MMF level-3 basic platform capabilities:

- Mobility
- Communications
- Situational awareness
- Load and unload a specific class of supplies
- Ability to avoid catastrophic loss

Finally, within the explicit context of the demonstration vignette, we assume that all five capabilities must be available to and demonstrable by each supply truck in the convoy to ensure that all trucks are capable of executing their respective supply delivery tasks. Ergo, the loss of any one (or more) of these capabilities by a truck would then preclude that truck from carrying out its respective resupply task.

As described in section 4.2.2, the System Capabilities Analytic Process (SCAP) provides a methodology for explicitly characterizing the capabilities demonstrated by the convoy trucks. In defining SCAP, Agan has observed that "when components are grouped into sub-systems, they will produce functions that will (collectively) provide the capability to complete the mission task."[1] This systemic grouping of components is accomplished via the use of fault trees, which are graph structures that express the logical relationship(s) between a system's function (or set of

[1] Agan, K. S. *An Emerging Methodology: The System Capabilities Analytic Process (SCAP)*; ARL-TR-5415; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, December 2010; p 6.

functions) and those constituent components within the system whose disabling will lead to the loss of that function.[2] Fault trees are generally represented as series-parallel digraphs. In use, fault trees are exploited to discover the effect that a change in state of the constituent components causes for the state of the system's functionality.

Within a SCAP application, the functional state of a component metric as used within a fault tree is binary in nature, where

- $component_x = 1$ indicates that system component X remains functional, while
- $component_x = 0$ indicates that system component X has been rendered dysfunctional.

Figure A-1 depicts the two most common component "building blocks" typically utilized within a generic fault tree logical structure. A serial component pathway (figure A-1a) is evaluated using the conjunctive AND (intersection) operator, wherein the functional loss of any single included component suffices to cut the source-sink pathway within the fault tree. Logically, this serial component pathway can be represented in the form

$$component_1 \wedge component_2 \,,$$

which is evaluated as a true statement (i.e., a value of 1) if and only if (iff) $component_1 = 1$ and $component_2 = 1$. On the other hand, a parallel component pathway (figure A-1b) is evaluated using the disjunctive OR (union) operator, wherein all included individual pathways must be cut (via the occurrence of component dysfunction) in order to cut the source-sink pathway within the fault tree. Logically, this parallel component pathway can be represented in the form

$$component_3 \vee component_4 \,,$$

which is evaluated as a true statement if $component_3 = 1$ or $component_4 = 1$. As long as an unbroken path can be traced through the entire fault tree from beginning to end, the system function represented by the diagram remains intact. However, if an unbroken path cannot be traced through the diagram, the associated system function has been lost (as well as some loss of system capability dependent upon the lost system function).

In the following sections, the SCAP methodology is applied to each of the six trucks in the supply convoy in order to formulate platform capabilities, as well as the operational readiness of a truck to perform its specific resupply mission task within the context of the demonstration scenario as a function of availability of platform capabilities required for task execution.

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[2] International Electrotechnical Commission. *Fault Tree Analysis*, edition 2.0; IEC 61025; Geneva, Switzerland, 2006.

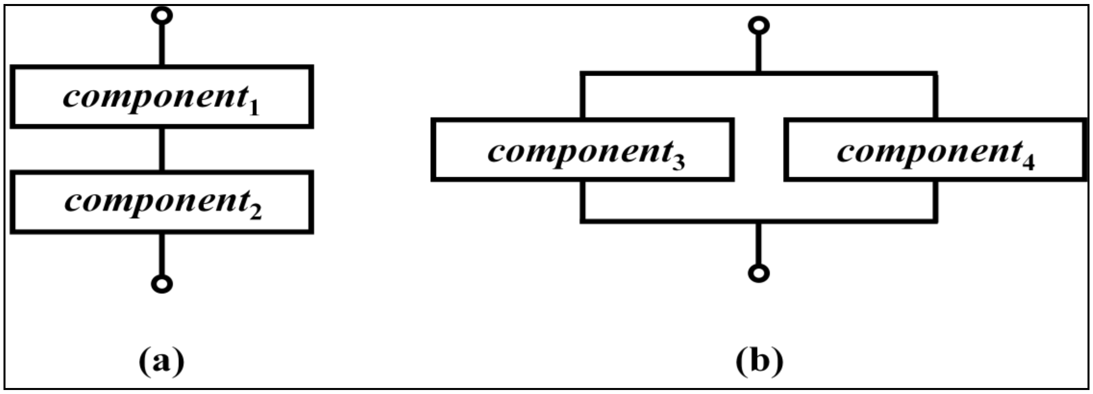

Figure A-1. Examples of generic fault tree logical structure: (a) components connected in a "series" relationship and (b) components connected in a "parallel" relationship.

A.1 Supply Truck Mobility Capability

The first platform capability we will define is *mobility*: the ability of a supply truck to move along on any type of reasonably level open terrain. For the n^{th} convoy truck, where $n = \{1, 2, 3, 4, 5, 6\}$, the state of the mobility capability is represented by the logical relation

mobilization_truck_n = *wheels_truck_n* & *transmission_truck_n* & *fuel_system_truck_n* & *fuel_tank_truck_n* & *engine_truck_n* & (*driver_truck_n* | *commander_truck_n*)

where *mobilization_truck_n* = mobility capability state associated with the n^{th} convoy truck, and

$$\left.\begin{matrix} wheels\_truck\_n \\ transmission\_truck\_n \\ fuel\_system\_truck\_n \\ fuel\_tank\_truck\_n \\ engine\_truck\_n \\ driver\_truck\_n \\ commander\_truck\_n \end{matrix}\right\} = \begin{matrix}\text{component and sub} - \text{system states within} \\ \text{the } n^{th} \text{ convoy truck.}\end{matrix}$$

The fault tree associated with this logical relation is depicted in figure A-2. We have assumed that for all supply trucks, the truck commander has been cross-trained to perform the driver's function should the latter be rendered dysfunctional and unable to perform his/her role. Also, for the purposes of illustrative clarity, the notional components and subsystems making up each of the supply trucks have been greatly simplified without any loss of generality, thus allowing us to directly map platform component and subsystem states directly to generalized capabilities. In a real system, the relationships between components, subsystems, platform functions, and platform capabilities would be of much greater complexity.

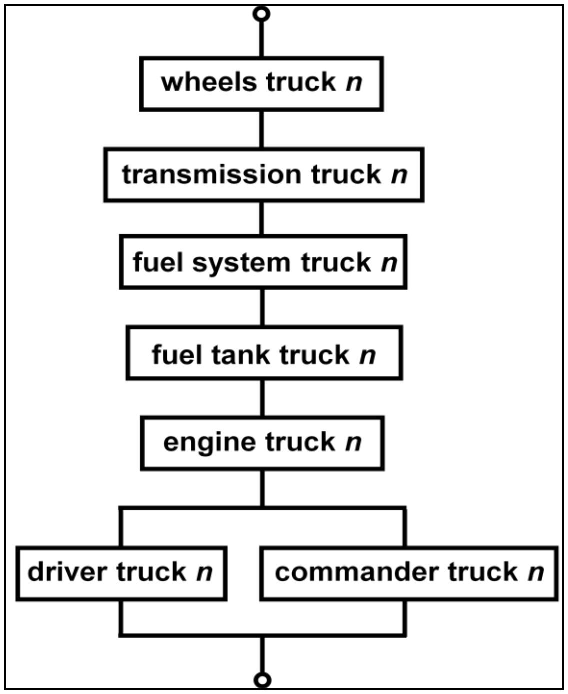

Figure A-2. Fault tree diagram illustrating the generalized mobility capability state associated with the n^{th} convoy truck.

A.2 Supply Truck External Communications Capability

Next, we define the *external communications* platform capability: the ability of a supply truck to both transmit and receive radio messages to and from other friendly platforms, including the other members of the supply convoy. For the n^{th} convoy truck, where $n = \{1, 2, 3, 4, 5, 6\}$, the state of the external communications capability is represented by the logical relation

external_comms_truck_n = (*voice_radio_truck_n* | *data_radio_truck_n*) & *power_system_truck_n* & *commander_truck_n*

where *external_comms_truck_n* = external communications capability state associated with the n^{th} convoy truck, and

$$\left.\begin{array}{c} voice\_radio\_truck\_n \\ data\_radio\_truck\_n \\ power\_system\_truck\_n \\ commander\_truck\_n \end{array}\right\} = \begin{array}{l} \text{component and sub} - \text{system states within} \\ \text{the } n^{th} \text{ convoy truck.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-3. We have assumed that for all supply trucks, the voice and data radio subsystems are able to provide redundant functionality to support the external communications capability.

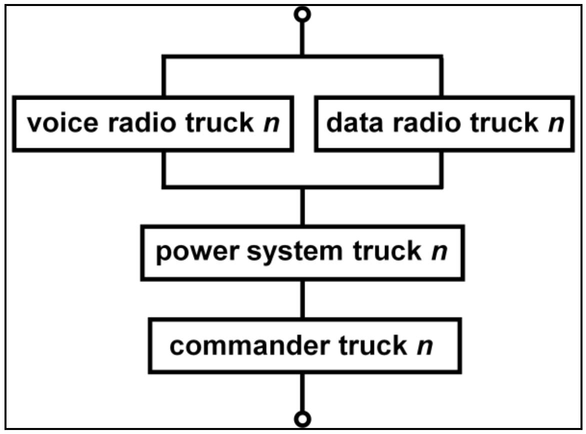

Figure A-3. Fault tree diagram illustrating the generalized external communications capability state associated with the n^{th} convoy truck.

A.3 Supply Truck Situational Awareness Capability

The third platform capability we define is *situational awareness*: the ability of a supply truck commander to dynamically perceive and understand an evolving operational situation within the surrounding environment external to the truck. For the n^{th} convoy truck, where $n = \{1, 2, 3, 4, 5, 6\}$, the state of the situational awareness capability is represented by the logical relation

situational_awareness_truck_n = data_radio_truck_n & fbcb2_truck_n & power_system_truck_n & commander_truck_n

where *situational_awareness_truck_n* = situational awareness capability state associated with the n^{th} convoy truck, and

$$\left.\begin{matrix} data\_radio\_truck\_n \\ fbcb2\_truck\_n \\ power\_system\_truck\_n \\ commander\_truck\_n \end{matrix}\right\} = \begin{matrix} \text{component and sub}-\text{system states within} \\ \text{the } n^{th} \text{ convoy truck.} \end{matrix}$$

The fault tree associated with this logical relation is depicted in figure A-4.

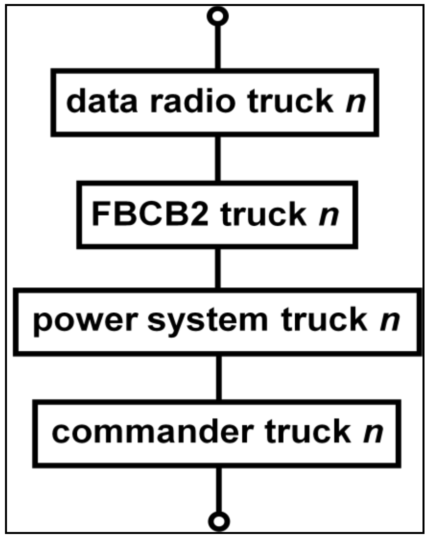

Figure A-4. Fault tree diagram illustrating the generalized situational awareness capability state associated with the n^{th} convoy truck.

A.4 Supply Truck Load/Unload Supplies Capability

Now, we define the *load/unload supplies* platform capability: the ability of a supply truck to both load and unload a specific class of military supplies as required by other friendly units. Given that this is specifically a logistics-oriented type of capability, a truck's ability to provide these functions is directly correlated to the class of supplies the truck is assigned to transport. In the following subsections, the "load/unload supplies" capabilities are functionally defined for those convoy trucks transporting class III, V, and VII types of supplies, respectively.

A.4.1 Class III Supplies

For the i^{th} convoy truck carrying class III supplies, where $i = \{1, 2, 3\}$, the state of the capability to load/unload such supplies is represented by the logical relation

load_unload_class_III_supplies_truck_i = *fuel_supplies_truck_i* & *forklift_truck_i* & *loader_truck_i*

where *load_unload_class_III_supplies_truck_i* = "load/unload class III supplies" capability state associated with the i^{th} convoy truck, and

$$\left.\begin{array}{c} fuel\_supplies\_truck\_i \\ forklift\_truck\_i \\ loader\_truck\_i \end{array}\right\} = \begin{array}{l}\text{component/sub} - \text{system and supply states within} \\ \text{the } i^{th} \text{ convoy truck.}\end{array}$$

The fault tree associated with this logical relation is depicted in figure A-5a.

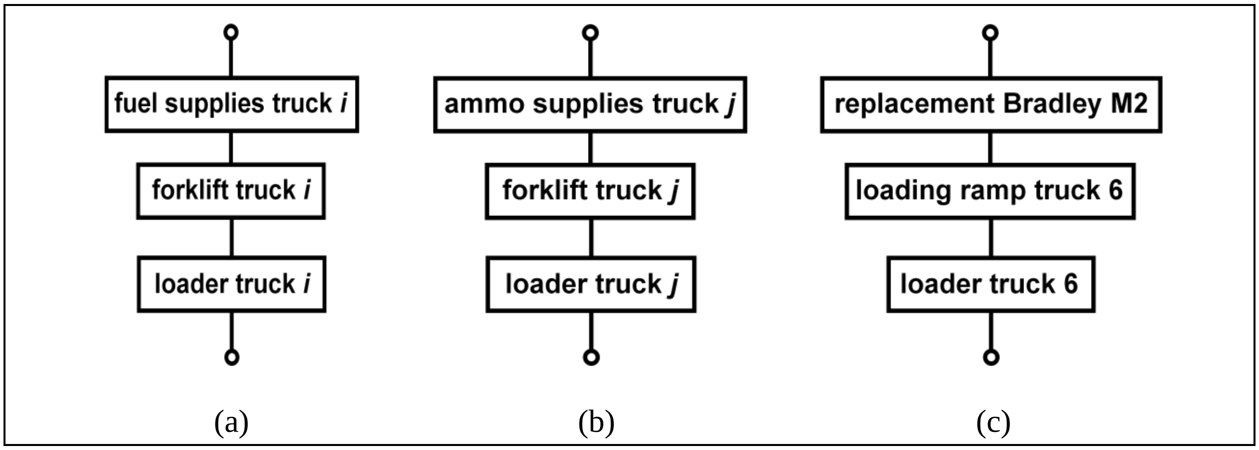

Figure A-5. Fault tree diagrams illustrating the generalized "load/unload supplies" capability states associated with (a) the i^{th} truck providing class III supplies, (b) the j^{th} truck providing class V supplies, and (c) truck 6 providing class VII supplies.

A.4.2 Class V Supplies

For the j^{th} convoy truck carrying class V supplies, where $j = \{4, 5\}$, the state of the capability to load/unload such supplies is represented by the logical relation

load_unload_class_V_supplies _truck_j = *ammo_supplies_truck_j* & *forklift_truck_ j* & *loader_truck_j*

where *load_unload_class_V_supplies_truck_j* = "load/unload class V supplies" capability state associated with the j^{th} convoy truck, and

$$\left.\begin{array}{c} ammo\_supplies\_truck\_j \\ forklift\_truck\_j \\ loader\_truck\_j \end{array}\right\} = \begin{array}{l} \text{component/sub} - \text{system and supply states within} \\ \text{the } j^{th} \text{ convoy truck.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-5b.

A.4.3 Class VII Supplies

Finally, for convoy truck 6 carrying class VII supplies (i.e., one replacement Bradley M2 ground vehicle), the state of the capability to load/unload such supplies is represented by the logical relation

*load_unload_class_VII_supplies _truck_*6 = *replacement_bradley_m2* & *loading_ramp_truck_*6 & *loader_truck_*6

where *load_unload_class_VII_supplies_truck_*6 = "load/unload class VII supplies" capability state associated with convoy truck 6, and

$$\left.\begin{array}{c} replacement\_bradley\_m2 \\ loading\_ramp\_truck\_6 \\ loader\_truck\_6 \end{array}\right\} = \begin{array}{l} \text{component/sub} - \text{system and supply states within} \\ \text{convoy truck 6.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-5c.

A.5 Supply Truck Avoid Catastrophic Kill Capability

Last, we define the *avoid catastrophic kill* platform capability: the ability of a supply truck to prevent an onboard volatile substance from igniting and subsequently destroying the truck when the substance explodes. The most common substances that can, upon ignition triggered by intense heat or shock, instantiate a catastrophic kill are vehicular fuel and onboard ammunition. Since the supply trucks in the convoy are not armored vehicles, we assume that the only means available to prevent catastrophic kills is for a truck to avoid situations where onboard fuel and ammunition could be subjected to enemy weapon fires. We also assume that fuel and ammunition components are rendered dysfunctional when they are ignited and subsequently explode. Thus, in the case of logistical supply vehicles, a platform's ability to avoid a catastrophic kill is often directly correlated to the class of supplies the vehicle is assigned to transport. In the following subsections, the "avoid catastrophic kill" capabilities are functionally defined for those convoy trucks transporting class III, V, and VII types of supplies, respectively.

A.5.1 Class III Supplies

For the i^{th} convoy truck carrying class III supplies (i.e., fuel), where $i = \{1, 2, 3\}$, the state of the capability to avoid catastrophic loss is represented by the logical relation

avoid_catastrophic_loss_truck_i = *fuel_supplies_truck_i* & *fuel_tank_truck_i*

where *avoid_catastrophic_loss_truck_i* = "avoid catastrophic loss" capability state associated with the i^{th} convoy truck, and

$$\left.\begin{array}{c} fuel\_supplies\_truck\_i \\ fuel\_tank\_truck\_i \end{array}\right\} = \begin{array}{l} \text{component/sub} - \text{system and supply states within} \\ \text{the } i^{th} \text{ convoy truck.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-6a.

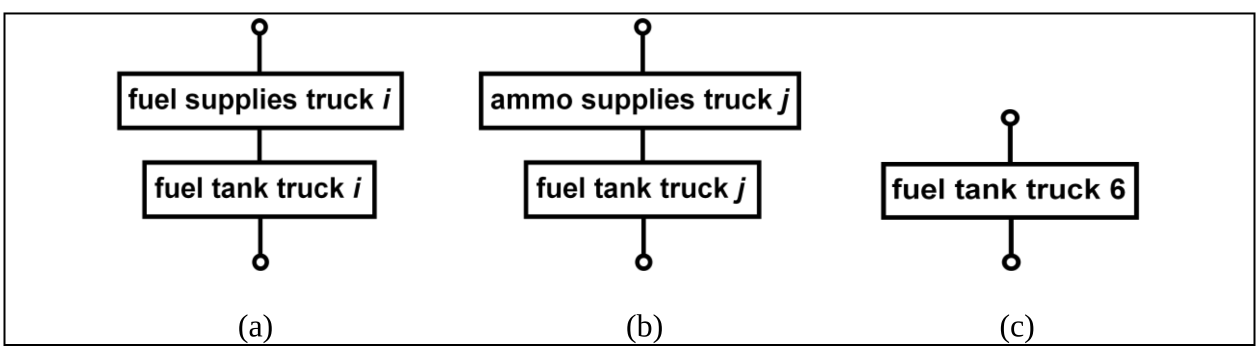

Figure A-6. Fault tree diagrams illustrating the generalized "avoid catastrophic loss" capability states associated with (a) the i^{th} truck providing class III supplies, (b) the j^{th} truck providing class V supplies, and (c) truck 6 providing class VII supplies.

A.5.2 Class V Supplies

For the j^{th} convoy truck carrying class V supplies (i.e., ammunition), where $j = \{4, 5\}$, the state of the capability to avoid catastrophic loss is represented by the logical relation

$$avoid\_catastrophic\_loss\_truck\_j = ammo\_supplies\_truck\_j \ \& \ fuel\_tank\_truck\_j$$

where *avoid_catastrophic_loss_truck_j* = “avoid catastrophic loss” capability state associated with the j^{th} convoy truck, and

$$\left.\begin{array}{c} ammo\_supplies\_truck\_j \\ fuel\_tank\_truck\_j \end{array}\right\} = \begin{array}{l} \text{component/sub} - \text{system and supply states within} \\ \text{the } j^{th} \text{ convoy truck.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-6b.

A.5.3 Class VII Supplies

Finally, for convoy truck 6 carrying class VII supplies (i.e., one replacement Bradley M2 ground vehicle), the state of the capability to avoid catastrophic loss is represented by the logical relation

$$avoid\_catastrophic\_loss\_truck\_6 = fuel\_tank\_truck\_6$$

where *avoid_catastrophic_loss_truck*_6 = “avoid catastrophic loss” capability state associated with convoy truck 6, and

$$fuel\_tank\_truck\_6 = \text{component/sub} - \text{system state within convoy truck 6.}$$

The fault tree associated with this logical relation is depicted in figure A-6c. Since we assume that the Bradley M2 cargo is being transported with an empty fuel tank (for safety reasons), the only component within truck 6 that could induce a catastrophic loss if energetically impacted (and thus igniting the fuel within) is its own fuel tank.

A.6 Convoy Readiness to Execute “Transport Supplies” Tasks

Once we have defined the five platform-level capabilities required for proper execution of the various “transport supplies” tasks assigned to specific supply convoy trucks, the corresponding capability states must be formally and logically mapped to a state indicating the operational readiness of each truck to perform its respective task. In the following subsections, the “readiness” states of the aforementioned “transport supplies” platform tasks are functionally defined for those convoy trucks transporting class III, V, and VII types of supplies, respectively.

A.6.1 Class III Supplies

Within the context of the demonstration vignette, the task “provide class III supplies” can only be executed by the i^{th} convoy truck, where $i = \{1, 2, 3\}$, if the following logical statement is true:

$R_{Class\ III}^{truck\ i}$ = *mobilization_truck_i* & *external_comms_truck_i* & *situational_awareness_truck_i* & *load_unload_class_III_supplies _truck_i* & *avoid_catastrophic_loss_truck _i*

where $R_{Class\ III}^{truck\ i}$ = task "readiness" state associated with the *i*th convoy truck, and

$$\left.\begin{array}{c} mobilization\_truck\_i \\ external\_comms\_truck\_i \\ situational\_awareness\_truck\_i \\ load\_unload\_class\_III\_supplies\ \_truck\_i \\ avoid\_catastrophic\_loss\_truck\ \_i \end{array}\right\} = \begin{array}{l} \text{capability states associated with} \\ \text{the } i^{th} \text{ convoy truck.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-7a. This relation implies that this specific task can be executed by the associated convoy trucks if and only if all of the above platform capability states associated with an individual truck uniformly evaluate to a logical value of "true."

A.6.2 Class V Supplies

Again within the context of the demonstration vignette, the task "provide class V supplies" can only be executed by the *j*th convoy truck, where *j* = {4, 5}, if the following logical statement is true:

$R_{Class\ V}^{truck\ j}$ = *mobilization_truck_j* & *external_comms_truck_j* & *situational_awareness_truck_j* & *load_unload_class_V_supplies _truck_j* & *avoid_catastrophic_loss_truck _j*

where $R_{Class\ V}^{truck\ j}$ = task "readiness" state associated with the *j*th convoy truck, and

$$\left.\begin{array}{c} mobilization\_truck\_j \\ external\_comms\_truck\_j \\ situational\_awareness\_truck\_j \\ load\_unload\_class\_V\_supplies\ \_truck\_j \\ avoid\_catastrophic\_loss\_truck\ \_j \end{array}\right\} = \begin{array}{l} \text{capability states associated with} \\ \text{the } j^{th} \text{ convoy truck.} \end{array}$$

The fault tree associated with this logical relation is depicted in figure A-7b.

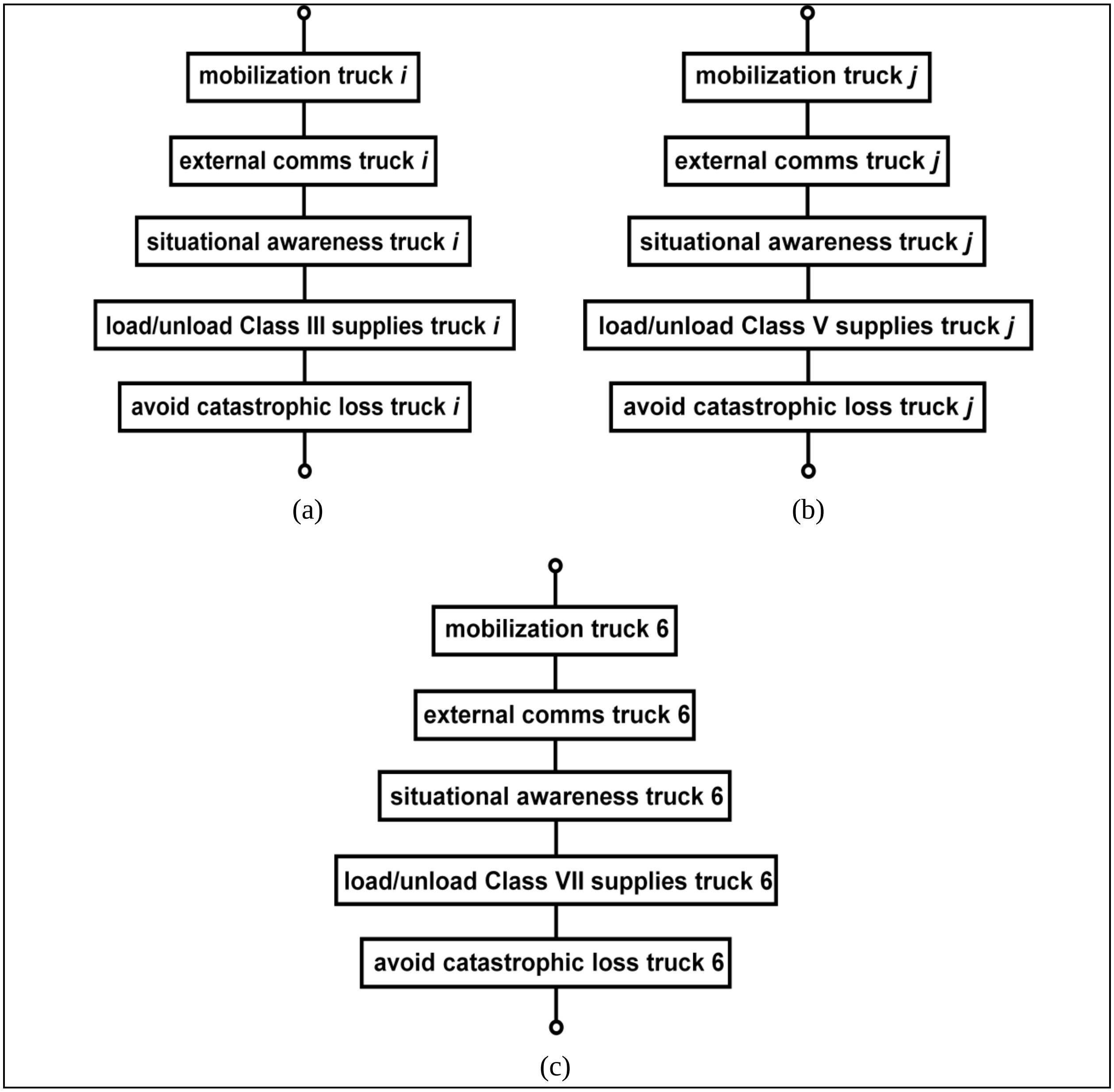

Figure A-7. Fault tree diagrams illustrating the generalized "provide supplies" task readiness states associated with (a) the i^{th} truck providing class III supplies, (b) the j^{th} truck providing class V supplies, and (c) truck 6 providing class VII supplies.

A.6.3 Class VII Supplies

Last, also again within the context of the demonstration vignette, the task "provide class VII supplies" can only be executed by convoy truck 6 if the following logical statement is true:

$$R_{Class\ VII}^{truck\ 6} = mobilization\_truck\_6\ \&\ external\_comms\_truck\_6\ \&\ situational\_awareness\_truck\_6\ \&\ load\_unload\_class\_VII\_supplies\_truck\_6\ \&\ avoid\_catastrophic\_loss\_truck\_6$$

where $R^{truck\ 6}_{Class\ VII}$ = task "readiness" state associated with convoy truck 6, and

$$\left.\begin{array}{c} mobilization\_truck\_6 \\ external\_comms\_truck\_6 \\ situational\_awareness\_truck\_6 \\ load\_unload\_class\_V\_supplies\ \_truck\_6 \\ avoid\_catastrophic\_loss\_truck\ \_6 \end{array}\right\} = \text{capability states associated with convoy truck 6.}$$

The fault tree associated with this logical relation is depicted in figure A-7c.

Appendix B. System Capabilities Analytic Process–Based Analysis of Situation No. 2 Within the Multithreaded Missions and Means Framework Demonstration

As described in section 4.2.2, the potential "situation no. 2" event branching that may occur within the multithreaded Missions and Means Framework (MMF) demonstration vignette involves the Blue supply convoy encountering several improvised explosive devices (IEDs) planted by Janazer-inspired insurgents within a small Ageorian village. We again employ the System Capabilities Analytic Process (SCAP) methodology to analyze the causal effects precipitated by these IEDs upon the capabilities demonstrated by the six vehicles in the convoy. Specifically, we use the system capabilities fault trees for the convoy vehicles (previously developed in appendix A) to track and trace how the IED-generated state changes to the components and subsystems making up the platforms in the Blue supply convoy negatively impact convoy task readiness levels.

This is explicitly depicted in figures B-1–B-10, which illustrate the functional status of individual Blue supply convoy trucks immediately prior to (figures B-1–B-6) and directly following (figures B-7–B-10) the IED attack. In these display windows associated with the agent-based modeling and simulation (ABMS) software, the right-hand column indicates the current state of all components within a platform (where, in this context, the term "component" refers to a constituent element of a system that cannot be further subdivided into two or more smaller elements); the left-hand column indicates the states of all SCAP elements associated with that same platform that directly depends upon current component states (i.e., subsystem, function, capability, and task readiness states).

In all cases, element states are binary in nature, where a green state indicates that an element is functional and available for use (a logical value of 1), and a red state indicates that an element is dysfunctional and not available for use (a logical value of 0).

The "dependent" states shown in the left-hand column of a platform system state window are systematically organized in accord with the logical equations and associated fault trees as defined for all supply convoy trucks in appendix A. Finally, for purposes of clarity, tables B-1 and B-2 summarize (from the detailed SCAP results presented in figures B-1–B-10) the system capability states and related task readiness states (respectively) for all platforms in the Blue supply convoy both immediately before and immediately following the IED attack.

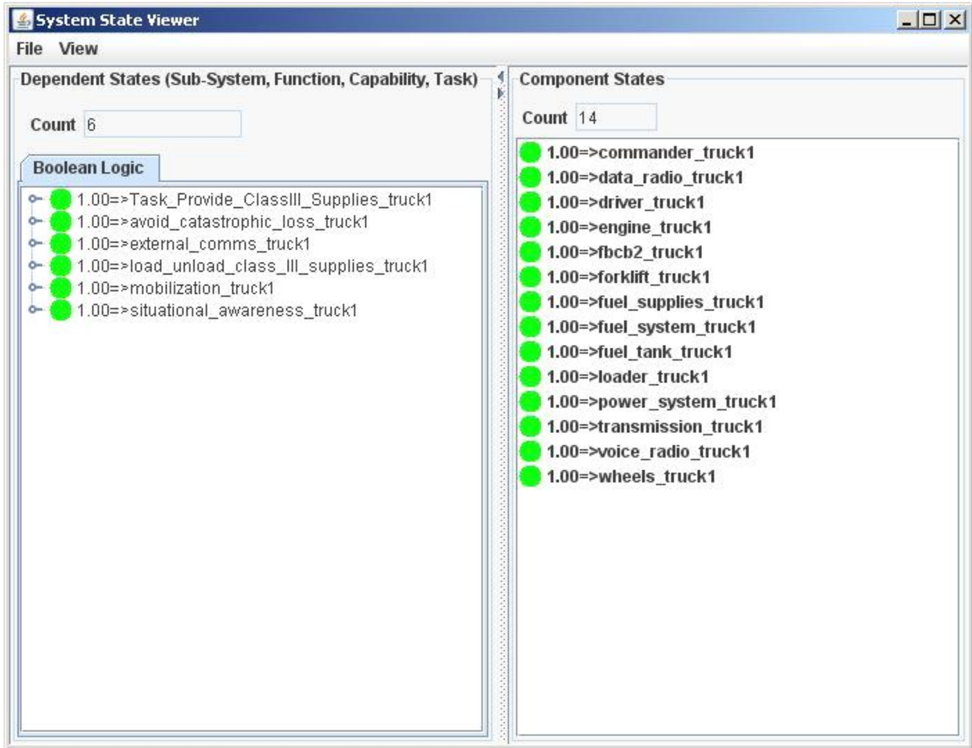

Figure B-1. Functional status of the individual Blue supply convoy trucks immediately prior to the IED attack: truck 1.

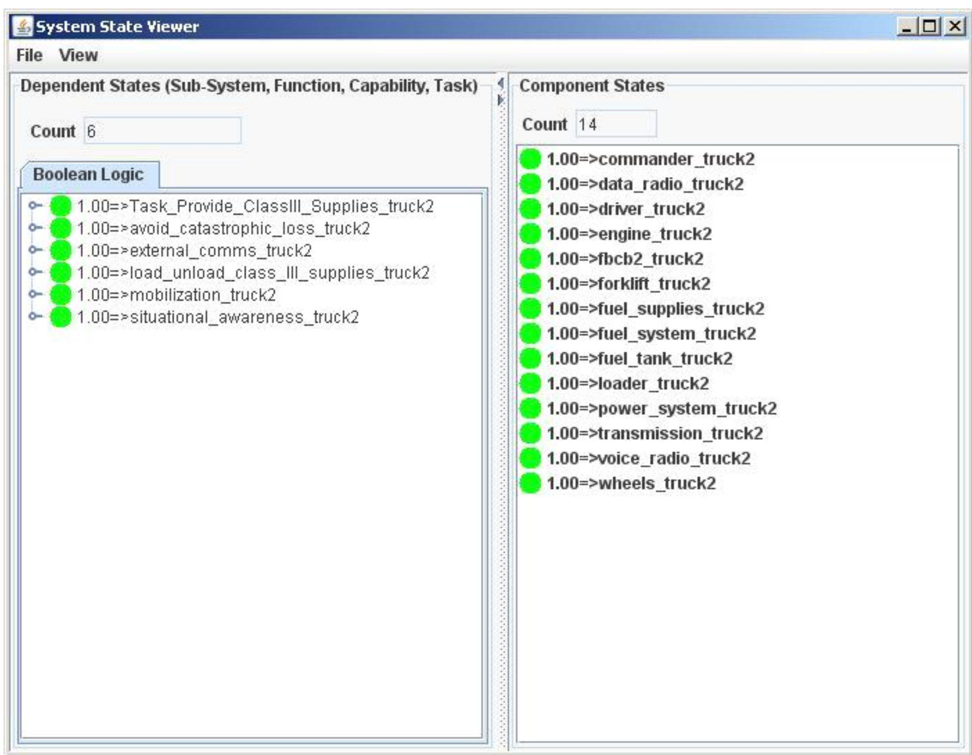

Figure B-2. Functional status of the individual Blue supply convoy trucks immediately prior to the IED attack: truck 2.

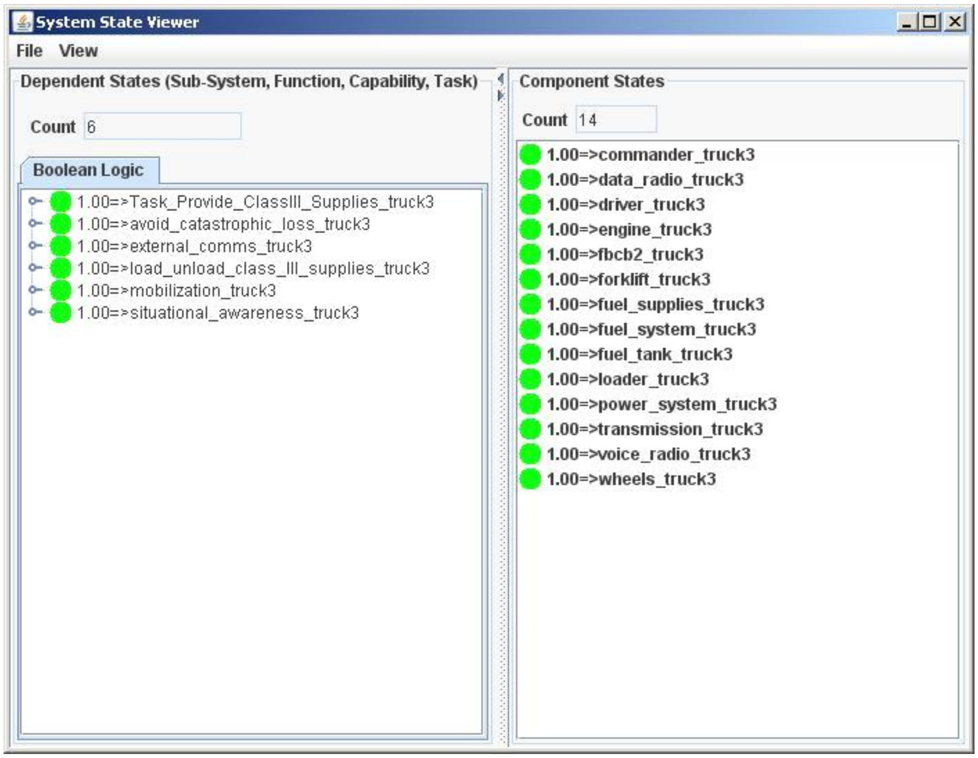

Figure B-3. Functional status of the individual Blue supply convoy trucks immediately prior to the IED attack: truck 3.

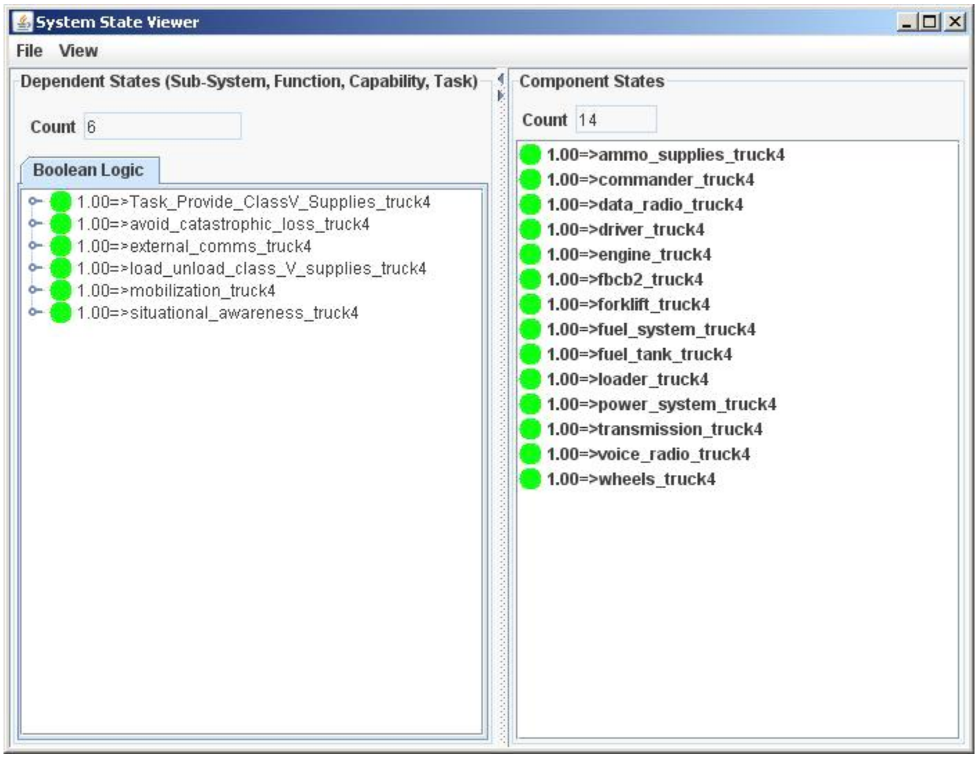

Figure B-4. Functional status of the individual Blue supply convoy trucks immediately prior to the IED attack: truck 4.

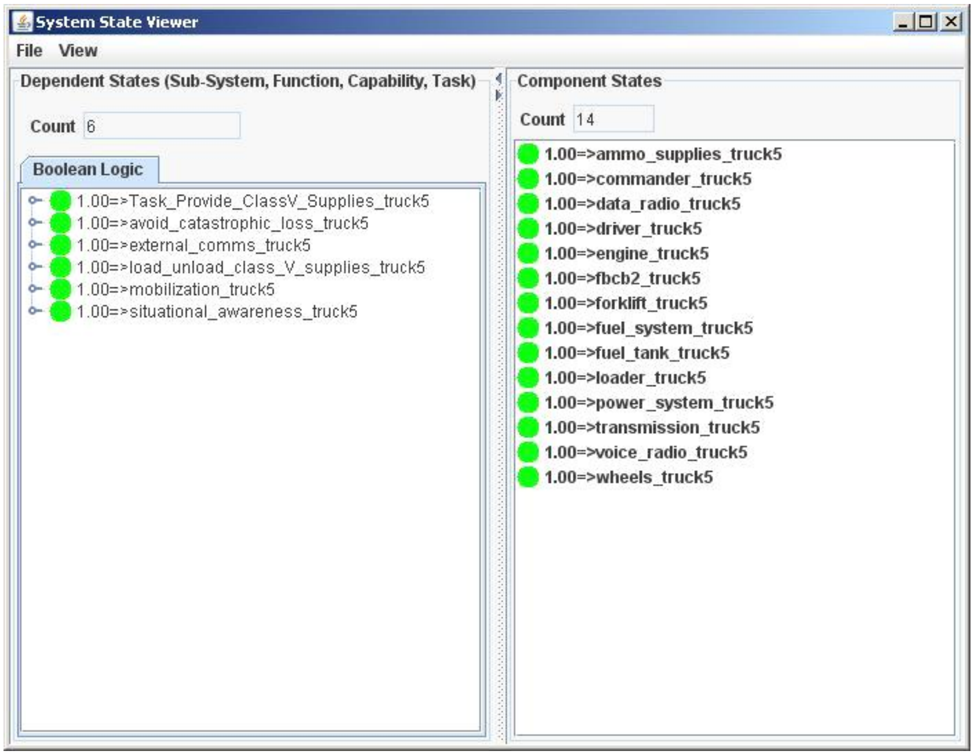

Figure B-5. Functional status of the individual Blue supply convoy trucks immediately prior to the IED attack: truck 5.

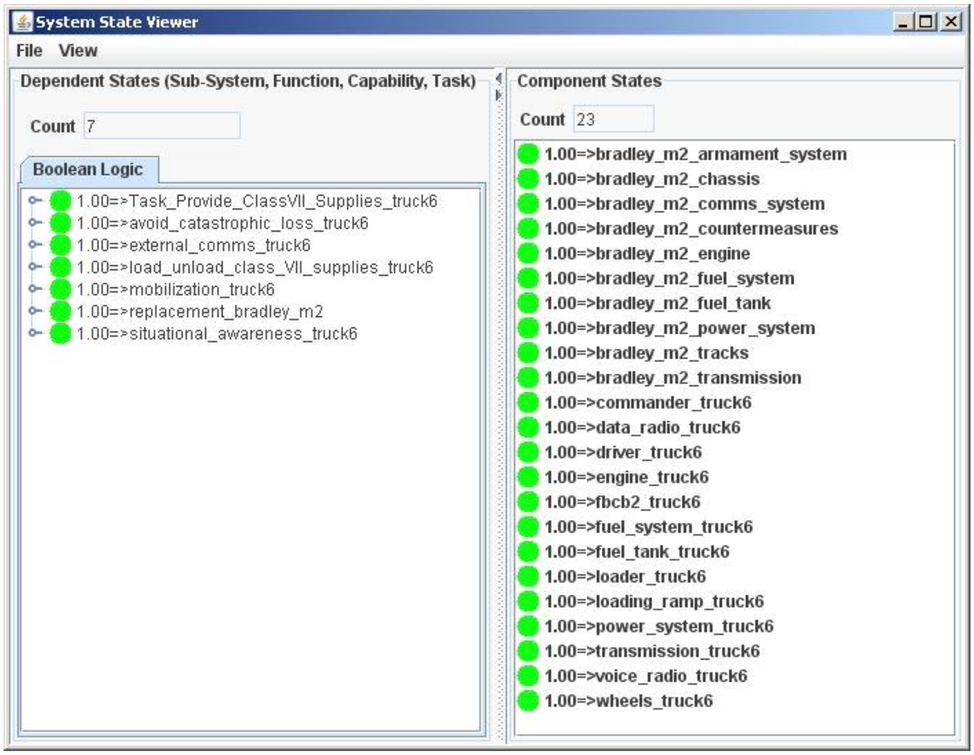

Figure B-6. Functional status of the individual Blue supply convoy trucks immediately prior to the IED attack: truck 6.

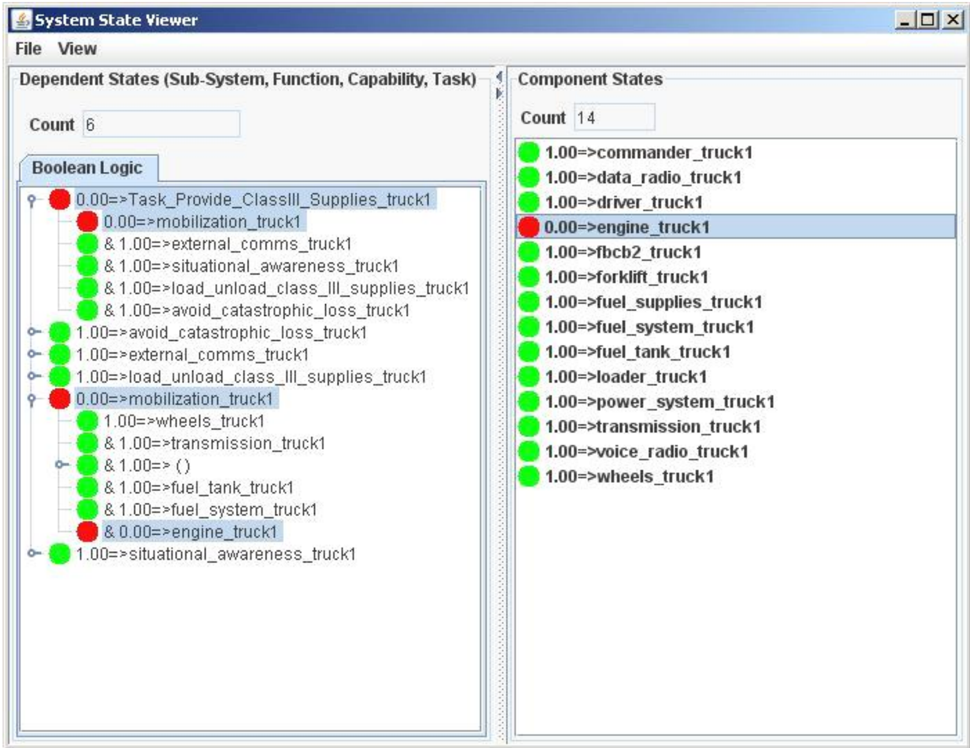

Figure B-7. Functional postevent status of specific Blue supply convoy trucks impacted by the IED attack: truck 1.

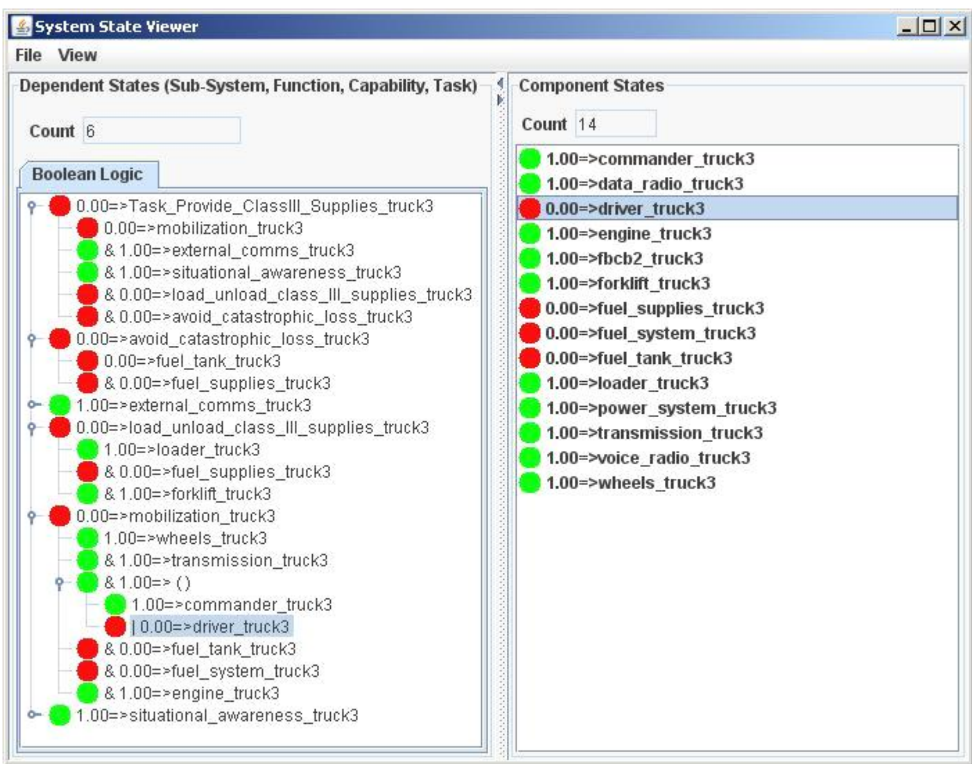

Figure B-8. Functional postevent status of specific Blue supply convoy trucks impacted by the IED attack: truck 3.

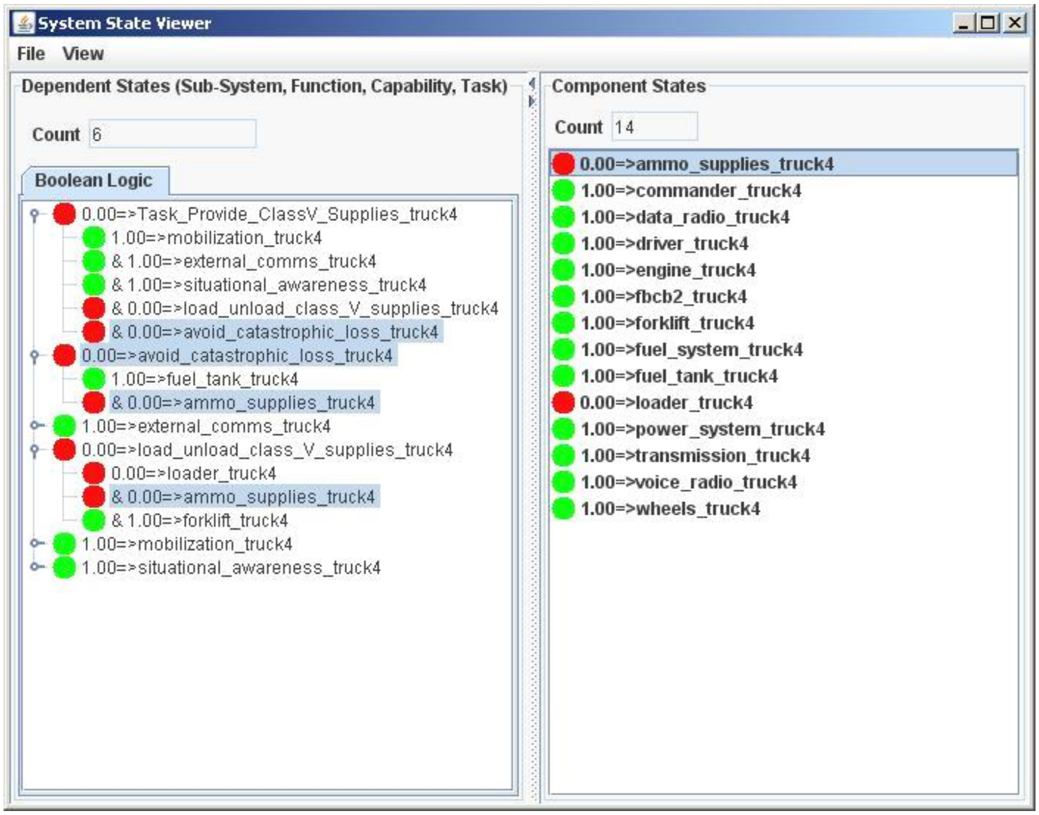

Figure B-9. Functional postevent status of specific Blue supply convoy trucks impacted by the IED attack: truck 4.

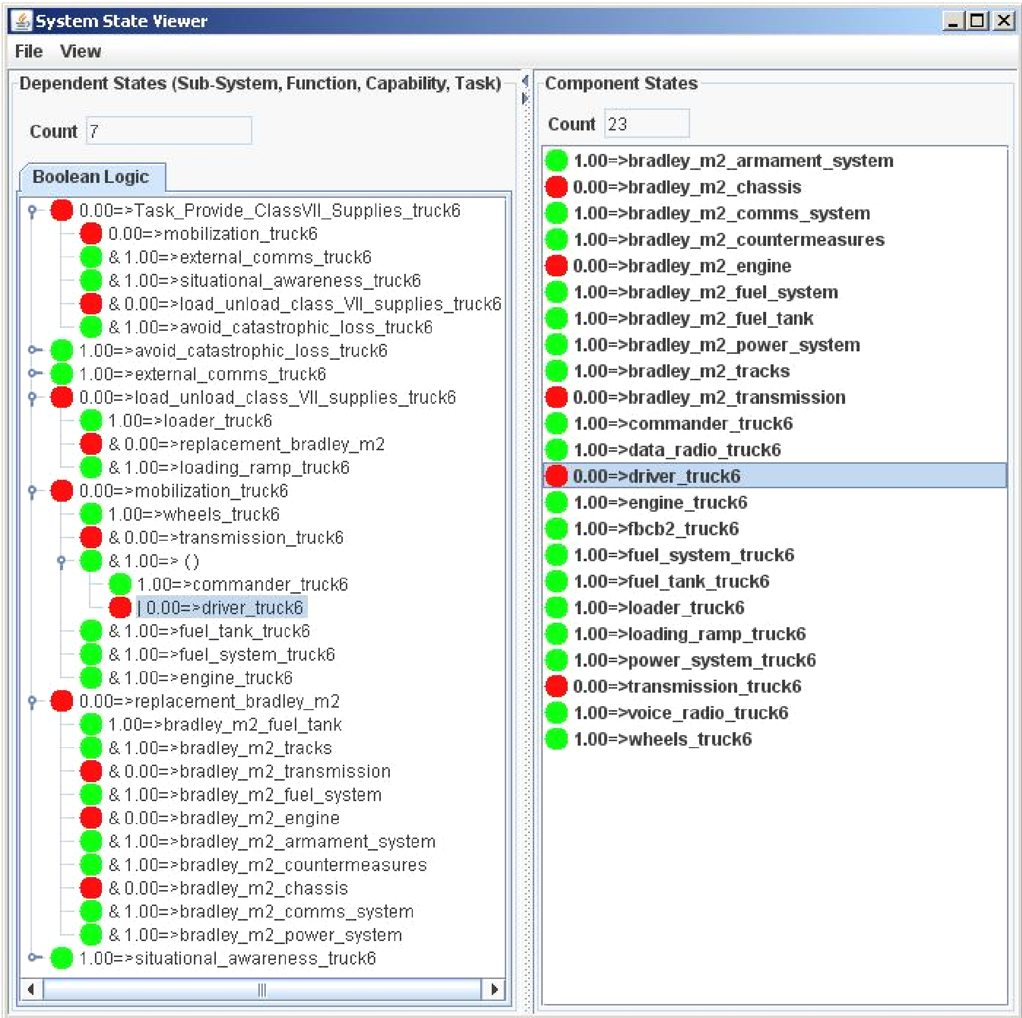

Figure B-10. Functional postevent status of specific Blue supply convoy trucks impacted by the IED attack: truck 6.

Table B-1. System capability states for all platforms in the Blue supply convoy both (a) immediately before and (b) immediately following the IED attack. In this table, columns are associated with specific convoy vehicles, while each row indicates the status of a system capability as associated with a specific convoy vehicle.

Platform Name → System Capabilities	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6
Avoid Catastrophic Loss	FUNC	FUNC	FUNC	FUNC	FUNC	FUNC
External Communications	FUNC	FUNC	FUNC	FUNC	FUNC	FUNC
Load/Unload Class III Supplies	FUNC	FUNC	FUNC	N/A	N/A	N/A
Load/Unload Class V Supplies	N/A	N/A	N/A	FUNC	FUNC	N/A
Load/Unload Class VII Supplies	N/A	N/A	N/A	N/A	N/A	FUNC
Mobilization	FUNC	FUNC	FUNC	FUNC	FUNC	FUNC
Situational Awareness	FUNC	FUNC	FUNC	FUNC	FUNC	FUNC

(a)

Platform Name → System Capabilities	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6
Avoid Catastrophic Loss	FUNC	FUNC	DYS	DYS	FUNC	FUNC
External Communications	FUNC	FUNC	FUNC	FUNC	FUNC	FUNC
Load/Unload Class III Supplies	FUNC	FUNC	DYS	N/A	N/A	N/A
Load/Unload Class V Supplies	N/A	N/A	N/A	DYS	FUNC	N/A
Load/Unload Class VII Supplies	N/A	N/A	N/A	N/A	N/A	DYS
Mobilization	DYS	FUNC	DYS	FUNC	FUNC	DYS
Situational Awareness	FUNC	FUNC	FUNC	FUNC	FUNC	FUNC

(b)

Notes: FUNC → functional; DYS → dysfunctional; N/A → capability not applicable to this system.

Table B-2. Task readiness states for all platforms in the Blue supply convoy both (a) immediately before and (b) immediately following the IED attack. As was the case with table B-1, columns are associated with specific convoy vehicles, while each row indicates the readiness status of a convoy vehicle to execute a particular mission task.

Platform Name → Mission Tasks	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6
Provide Class III Supplies	READY	READY	READY	N/A	N/A	N/A
Provide Class V Supplies	N/A	N/A	N/A	READY	READY	N/A
Provide Class VII Supplies	N/A	N/A	N/A	N/A	N/A	READY

(a)

Platform Name → Mission Tasks	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6
Provide Class III Supplies	NOT READY	READY	NOT READY	N/A	N/A	N/A
Provide Class V Supplies	N/A	N/A	N/A	NOT READY	READY	N/A
Provide Class VII Supplies	N/A	N/A	N/A	N/A	N/A	NOT READY

(b)

Notes: READY → system has sufficient capabilities as required to execute task; NOT READY → system lacks sufficient capabilities as required to execute task; N/A → task not applicable to this particular system.

As can be observed in figure B-1, all constituent components making up each of the six supply convoy trucks are in a functional “green” state immediately prior to encountering the planted IEDs. Consequently, all dependent SCAP states associated with each platform also indicate a “green” status, implying that all mission tasks assigned to the convoy can be executed given that all platform capabilities required for task execution are currently available for use. On the other hand, as portrayed in figure B-2, the conversion of key critical platform components in convoy trucks 1, 3, 4, and 6 from a functional state of “green” to “red” immediately subsequent to convoy interaction with the planted IEDs consequently also renders the task readiness status of these four trucks into an operational state of “red.” This task readiness degradation occurs because the truck components rendered dysfunctional by IED interactions all contribute to vehicle capabilities that are required to facilitate mission task execution by the impacted convoy trucks. Thus, loss of these components directly precludes a truck’s ability to perform actions required to properly accomplish a task. As a result, the logistical resupply mission assigned to the convoy can no longer be executed, necessitating all associated commanders involved with this mission to coordinate and replan accordingly.

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List of Symbols, Abbreviations, and Acronyms

ABMS	agent-based modeling and simulation
AO	area of operations
APOD	aerial port of debarkation
ASC	Army Sustainment Command
BCT	brigade combat team
C2	command and control
COA	course of action
CSC	convoy support center
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities
EBAL	Enterprise Based Approach to Logistics
ESC	Expeditionary Sustainment Command
FRAGO	fragmentary order
GUI	graphical user interface
IED	improvised explosive device
JFC	Joint Force Commander
JOA	Joint Operations Area
MEU	Marine Expeditionary Unit
MFLC	Modular Force Logistics Concept
MMF	Missions and Means Framework
OPFOR	Opposing Force
OWNFOR	Own Force
RSO	reception, staging, and onward
SCAP	System Capabilities Analytic Process
SOF	Special Operational Forces

SoS	system of systems
SPO	support operations
SPOD	sea port of debarkation
TAA	tactical assembly area
TSB(D)	Theater Sustainment Brigade Distribution
TSB(O)	Theater Sustainment Brigade Opening
TSC	Theater Sustainment Command

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